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# BACHELOR THESIS

## Improvement of a magneto- active polymer pump

Bachelor of Biomedical Engineering

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## ABSTRACT

In this thesis, three coils are controlled and given a sinusoidal magnetic field in order to open and close a magneto-active polymer actuator which can work as a peristaltic pump. The thesis is divided in three parts:

The first one contains a Codesys program and an electrical circuit where Analog Output Wago Module 750 556 is used. The software program has as an output a sinusoidal wave which has to be amplified. This is done in the electrical circuit.

The second part is also the design of a Codesys circuit and an electrical circuit using the Digital Output 750 502 module in order to control the three magnet coils. The Codesys Output has as an output a pulsed signal and using the pulse width technique the magnetic field can be controlled.

The last part is the tests of different pulsed signal Codesys programs. The frequency and the signal pulsed are not the same between the software programs. The behaviour of the peristaltic pump is analysed and compared to different programs.

Conclusions are extracted from the results of the tests and from the development of the electrical circuits and software programs.

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## 1. INTRODUCTION

Nowadays, biomedical engineering is changing and evolving so fast. There are so many new applications in order to improve people's life and to solve problems.

From one part, magnetic field applications have been applied to a lot of different fields, for example in the car industry, in a lot of production processes, in engines or in the telecommunications world. So some applications can be and actually have already been applied in the medicine. For example magnetic resonance imaging is used in radiology to know the anatomy and the physiological process of the body in health and disease. Also magneto therapy has started to be used in the last years because it has been proved that it has a lot of curative properties for cells and it's commonly used in physiotherapy.

From the other side, serious problems of a lot of patients all around the world are related in blood transportation. Veins and arteries can suffer aneurysm, which is an abnormal dilatation of the tube's wall. There are a lot of possible causes for an aneurysm to occur, currently they are being investigated.

Another sever problem for a person could be an artery or vein embolism which is an obstruction made by a plunger (like a blood clot, a fat drop, water bubble, bacteria pile, carcinogenic cells, etc.)

Other kind of problem of blood transportation could be that the tube breaks because it cannot hold the inner pressure, there is a defect in the wall tube or something external breaks the artery or the vein.

All this kind of problems can have really bad consequences for the person even it can bring someone to death. So it would be a huge step for medicine to solve this problem.

In the following bachelor thesis, a Magneto-Active Polymer (MAP) tube project in Ostbayerische Technische Hochschule Regensburg (OTHReg) is joined. This MAP tube acts as a fluid pump using magnets and in the future it might work as blood transporter implanted in human bodies. A lot of problems related in blood transportation could be solved.

## 2. GOAL

The goal of the project is to help the already existing project to develop the MAP peristaltic pump formed by the Prof. Dr. Gareth Monkman (OTHR) and Andreas Diermeier as a Research Assistant in Mechatronics Research Unit in Ostbayerische Technische Hochschule Regensburg. The steps followed in this bachelor thesis are not well defined at the beginning because the magneto-active polymer tube project is currently not well defined. So after every little step is done the next one will be defined. Because some problems can be found during the project so the process will be adapted to these problems or unpredicted things.

Some electrical circuits and software programs will be designed in order to feed three coils with three different current phases. The goal is to create a magnetic sinusoidal wave so that the MAP tube constricts and opens in a sinusoidal way. Some tests will be done with the programs and circuits designed. The results will be analysed and conclusions will be extracted.

### 3. PREVIOUS PROJECT AND RESEARCH

#### 3.1. Introduction

First of all is important to know what the project of the magneto-active polymer tube is about. All the steps that have already been done, what is currently being done and what is planned to be done. To do this, some meetings are needed with Professor Monkman and Andreas Diermeier. These meetings are also useful to get to know each other inside the members of the project, to decide the goal of the bachelor thesis and to get introduced with the rules and work dynamics in OTH.

Some research and some studying about magneto active polymer tubes has already been done. Actually two Scientific Paper has been published called *Magneto-active polymer actuator* and *Magneto-active polymer tube actuator*. Here is attached a short summary of both.

#### 3.2. Magneto-active polymer actuator paper

Magneto-active Polymer (MAP) are similar to magneto-rheological fluids and they contain micro-particles that react when submitted to a magnetic field. These micro-particles are in an elastic polymer matrix. When magnetic field is applied, mechanical and electrical changes appear. It can produce changes in Young's modulus over 1E6%.

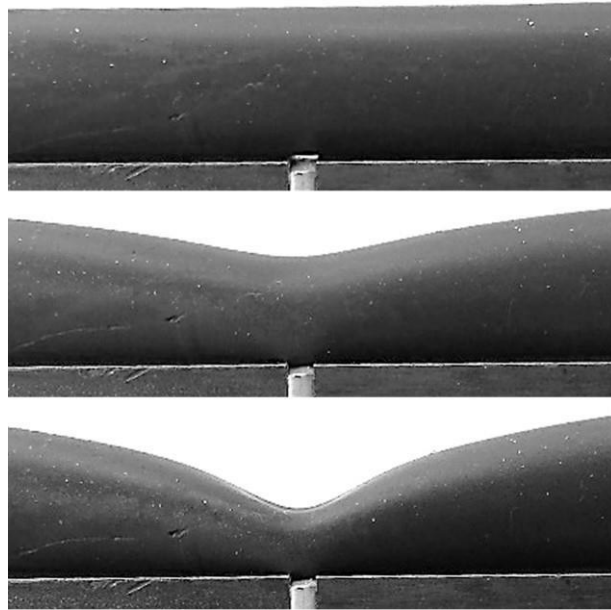
Current research focuses on controllable compliance (the facility measurement of a structure or a substance of being deformed) of MAP volumes and forms. Depending on the degree of magnetic field homogeneity with the magneto-rheological effect, magnetostriction and magneto deformation are observed.

MAP with piezoelectric devices allows a high energy conversion rate by adjusting the MAP load through a controlled magnetic field. An annular shaped magneto active elastomer (MAE) body expands annularly because of the influence of an applied magnetic field, so the gap inside is closed. The aim of this research is to establish and control hydraulic flow by MAP controlled systems.

MAP is composited by a polymer matrix and a suspension of magnetically susceptible micro-particles. Silicones, which are available with different viscosities and hardness, might be used for the matrix.

Carbonyl iron powder ( $\text{Fe}(\text{CO})_5$ ) "CIP SQ" (BASF) is used as the magnetic particles with a defined size distribution of 3.9-5.0 $\mu\text{m}$ .

Under the influence of an applied magnetic field, the tube is strongly deformed and constricted as shown in figure 1.



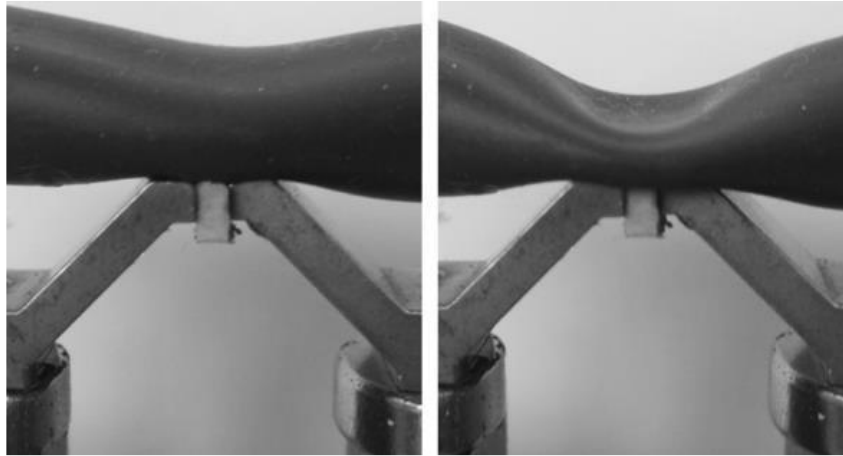
**Figure 1. MAP tube**  
**a) without B-field**  
**b) with B-field supplied by a electro magnet ( $B=200\text{mT}$ )**  
**c) with B-field supplied by a electro magnet ( $B=450\text{mT}$ )**

The constriction forces depend on the nature of the MAP and the field strength. In this research constriction is optimized for hydraulic valve suitability. Furthermore, a pulsed magnetic field will be used for pumping applications.

Due to its strong elasticity, MAP is used in the reproduction of systolic medical functions, such as Windkessel effect. This can help to investigate or solve several common arterial diseases, for example an aneurysm which is a localized arterial dilatation could be replaced by a MAP tube induced to a pulsed magnetic field.

Tests with a simple magnetic circuit were carried. The field is maximized in the 1.5mm air gap where the annular constriction of the MAP tube is carried. To keep closed the tub a magnetic flux of 450 mT is needed which consumes 7 Watts.

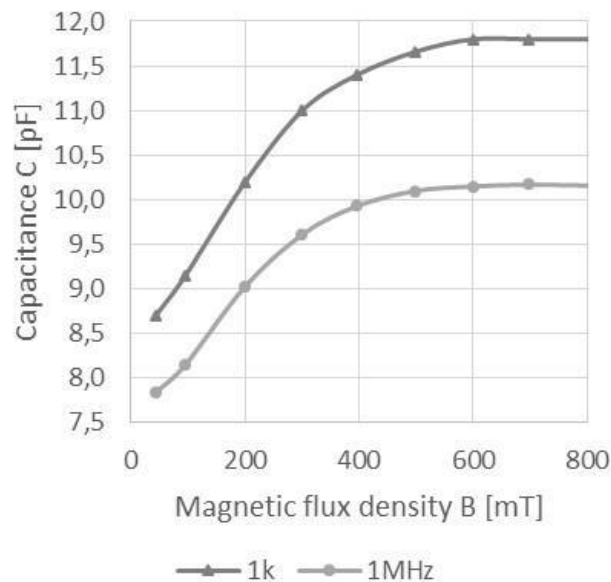
An alternative is to use NdBF<sub>e</sub> permanent magnets so the consumption is reduced. A permanent magnetic field is provided which can be negated by a short induced magnetic pulse. It allows the “normally closed” and “normally open” valves design, as can see observed in figure 2.



**Figure 2:** MAP tube open (left) and “normally closed” (right).

The MAP actuators need to be observed, so sensors into the MAP can be integrated such as strain gauges, Hall sensors or piezoelectric elements.

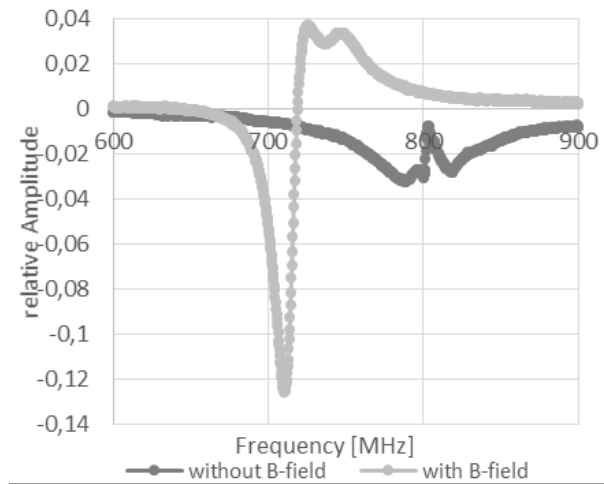
Also mechanical and electrical MAP characteristics could be used as the measurand because both change under the influence of an applied magnetic field. Though the dielectric constant of the polymer does not change, the distribution and proximity of the ferrous particles can. This results in an apparent change of the electrical capacitance value as shown in figure 3. For this the MAP sample was mounted in the gap between the yoke of two electromagnetic coils. Electrical capacitance was measured by a LCR meter (GW INSTEK: LCR800G) at a range of frequencies. The magnetic flux was controlled by current and was measured by a Gauss Meter (Lake Shore: 455 DSP + HMMT-6J04-VR).



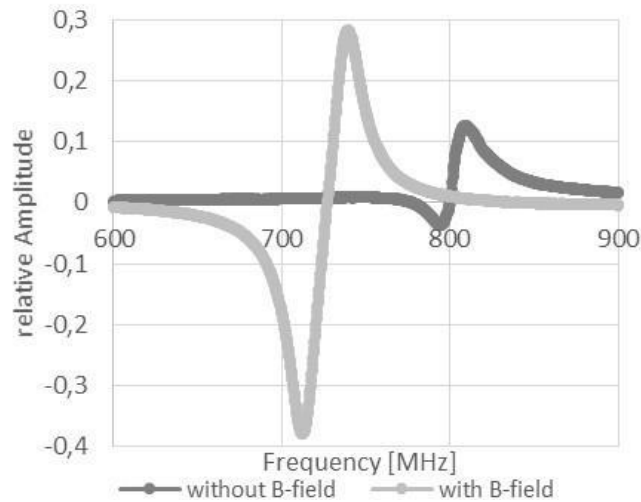
**Figure 3.** Capacitance of MAP sample under influence of magnetic field.



Inductance is also measurable. Figure 4 and 5 show the transfer function for no magnetic flux density applied and for 200 mT applied. In figure 4 the sample contains 5% of magnetic content by weight and 27% in figure 5. Measurements were made on a half-bridge with a Vector Network Analyser (Rhode & Schwarz ZND).



**Figure 4. MAP with 5wt. 5% transfer function.**



**Figure 5. MAP with 27wt% transfer function.**

As shown in figure 4, a number of resonances can be observed, which would not be visible in a first order system (such as RC) with monotonic decay.

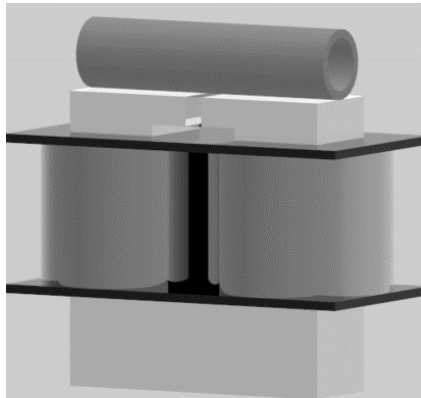
### 3.3. Magneto-active polymer tube actuator paper

The current article has the same test as the *Magneto-active polymer actuator* but it also has a FEM-Simulation of the tube actuator and a Peristaltic Pump test.

#### 3.3.1. FEM- Simulation

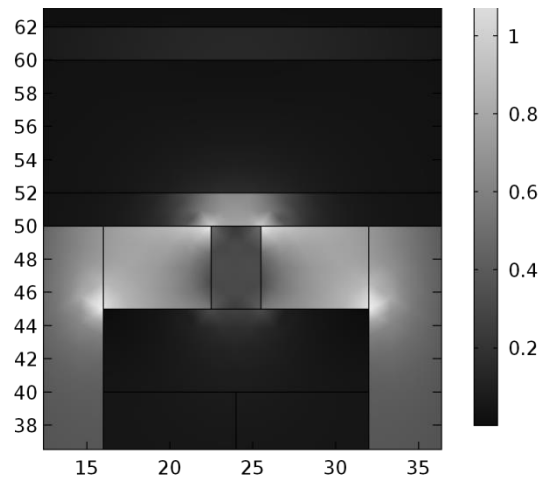
The finite element method (FEM) is a numerical method for solving problems of engineering and mathematical problems. It subdivides the big problem into small parts that which are called finite elements. The simple equations that model these finite elements are assembled into larger system of equations that models the whole problem. FEM uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function.

A FEM using Comsol Multiphysics was used to analyse and optimise the yoke design. It is based on the three-dimensional CAD model of the magnetic circuit, as shown in figure 6, consisting of an iron yoke with a 3mm air-gap, which is filled with an acryl material. On top of the yoke, a MAP-tubular device is mounted with a diameter of 9mm and a wall thickness of 1.5mm.



*Figure 6. 3 CAD model of the used yoke design.*

But in order to reduce FEM solving time, a two dimensional model was conducted. A stationary magnetic field was used to investigate the magnetic flux in the yoke and MAP tube, caused by two electric coils. The magnetic flux is induced to the MAP tube.



**Figure 7. Surface magnetic flux density at the gap [mT].**

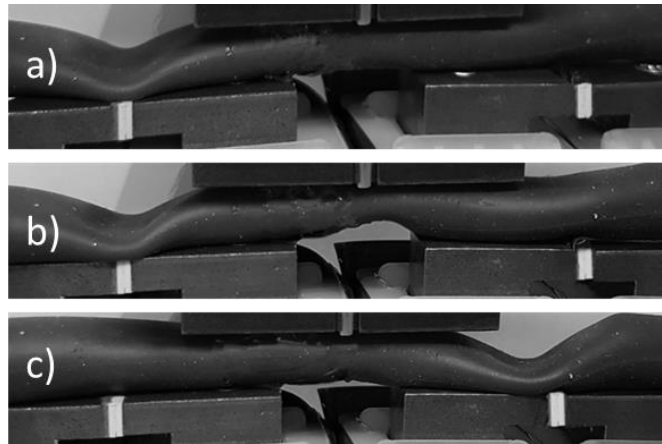
A mechanics simulation is coupled to the magnetic simulation by the Maxwell surface stress tensor which allows a simulation by the Maxwell surface stress tensor which led a simulation of the tube's surface displacement. Therefore, mechanical properties of the MAP material had to be included in the FEM material database. Elastic modulus and shear modulus of the MAP compound depend on the magnetic flux density. They were measured by an oscillation rheometer (Anto Paar MCR 301) with a special magnetorheological cell and inserted to the FEM database by interpolated curves.

The FEM simulations of the yoke lead to an optimized system design and an improved closing of the annular tubing by higher flux density. Consequently, a valve application based on MAP-tube is possible.

### **3.3.2. Peristaltic pump**

Current research concentrates on a new pump system. Peristaltic pumps use positive displacement for pumping the fluid and if using magnetic fields for tube constriction, deformation is without mechanical friction.

Three magnetic circuits were assembled with an offset thus sectional constriction of the MAP-tube is possible. Each cycle consist of six ON/OFF phases, where coil switching is done by Gray-code method.



**Figure 8. Peristaltic pump –a) phase I, b) phase II, c) phase IV.**

The system allows in a peristaltic manner. The control system has to be optimized but the pumping function is proved.

## **4. Sinusoidal wave with an amplification electrical circuit**

### **4.1. Introduction and background**

What is asked in order to develop more the MAP-tube pump project was to reprogram the coils that were programmed with the function ON/OFF to a sinusoidal magnetic field, so that the tube will contract in a softer way than the current one and the consequences will be analysed.

The best way to achieve it was by PLC programming. A Wago PLC 750-8202 Ethernet Controller programmed by CoDeSys V2.3 with special Wago target definitions. Also WAGO connector clamps 750-556 DC-Drive Controller 24V/5A and 750-501 2-Channel Digital Output Module 24 V DC will be used.

### **4.2. Material used**

#### **4.2.1. WAGO PLC 750-8202**

A Programmable Logic Controller (PLC) is a type of computer used in automatic engineering or industrial automation for automating electromechanical processes. PLC is used in many industries and machines and they are designed with multiples input and output signals.

The controller WAGO 750-8202 (PFC200 CS 2ETH RS) is an automation device, which perform control tasks of a PLC, and is suitable for mounting on a DIN rail and stands out on account of its various interfaces.

It is possible to connect all available I/O modules of the WAGO-I/O-SYSTEM 750 (750 and 753 series) to the controller, allowing it to internally process analog and digital signals from the automation environment, or to supply these signals to other devices.

Automation tasks can be executed in all IEC 61131-3 compatible languages with the WAGO-I/O-PRO with the runtime set CoDeSys 2.



**Figure 9. WAGO PLC 750-8202**

#### **4.2.2. CoDeSys V2.3**

CoDeSys (stands for Controlled Development System) is a complete development environment for the PLC. It puts a simple approach of the powerful IEC language at the disposal of the PLC programmer. Use of the editors and debugging functions is based upon the proven development program environments of advanced programming languages (such as Visual C++).

The CoDeSys will be controlled from Toshiba laptop with operational system Windows 10.

#### **4.2.3. WAGO Connection clamps**

In order to control the electromagnets different WAGO connector clamps have been used:

- 750-501 2-Channel Digital Output Module 24 V DC
- 750-556 2-Channel Analog Output;  $\pm 10$  VDC
- 750-600 End Module

#### **4.2.4. Function generator**

The function generator used is the Agilent Technologies 33210A Function/Arbitrary Waveform Generator. It is the latest addition to the 332XX family. Waveforms are generated using direct digital synthesis (DDS) technology which creates stable, accurate low distortion sine waves as well as square waves with fast rise and fall times up to 10 MHz and linear ramp waves up to 100 kHz.

#### 4.2.5. DC Power Supply

The DC Power Supply used to give current to the circuit is the *TTi EL302RT Triple Power Supply*. It is the ideal solution for users requiring a good manual control, linear regulated bench power supply of low to medium power. It offers dual displays, high resolution control and metering, remote sensing, dc output and switches.

#### 4.2.6. Oscilloscope

The oscilloscope used is the *Tektronix DPO 2014 Digital Phosphor Oscilloscope*. Offering up to 200 MHz bandwidth and 1 GS/s sample rate, the DPO2000B Mixed Signal Oscilloscope Series from Tektronix delivers advanced debug features at an entry-level price. Quickly find and diagnose problems in complex designs with up to 20 channels for analyzing analog and digital signals. With a deep record length of 1 Mpoints standard on all channels, the MSO/DPO2000B lets you capture long windows of signal activity while maintaining fine timing resolution.

#### 4.2.7. RCL meter

The RLC meter used is the PM 6303. It can be used for measurements of resistances, capacitances and inductances. Providing auto-function and auto-ranging facility the instrument allows fast and high precision measurements of passive components over a wide range.

The component under test is directly connected to the instruments via two-terminal. The measurement result, a numerical value, dimension and the equivalent-circuit symbol is immediately displayed on a large 4-digit liquid-crystal display (LCD), updated at a rate of two measurements per second.

#### 4.2.8. NPN Transistor

A S2000N NPN triple diffused mesa type transistor is used. It is used to amplify the current output of the PLC. The PLC output will be connected to the base and the amplified current will be in the collector.

Another transistor is used with higher power dissipation. It is the 2N3055 Mospec Semiconductor.

#### 4.2.9. Others

Some other electronic devices like wires, boards, resistors will be used to design the electrical circuits.

A Toshiba laptop with Windows 10 as a operational system.

Huawei P10 as a video camera for tests.

### 4.3. CoDeSys sinusoidal output wave program

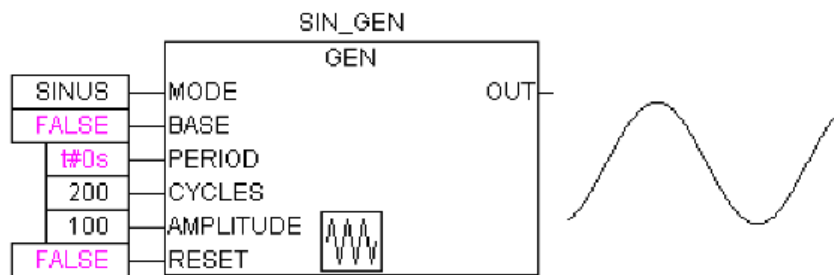
#### 4.3.1. Introduction

The goal is to have an output function signal of 2 A with a sinusoidal wave form. The first idea was to program with CoDeSys V2.3 a function from the Util.lib library lib (so it will have to be uploaded to the Codesys program) that has a sinusoidal output signal which would be directly connected to the coils.

The program can be founded in the annex.

#### 4.3.2. Codesys background

The sinusoidal wave was created by the function generator *GEN*.



**Figure 10. Example of the Function Block Gen.**

The inputs are:

- **MODE:** Describes the type of the function that should be generated.
- **BASE:** Defines whether the cycle period is really related to a defined time (BASE=TRUE) or whether it is related to a particular number of cycles, which means the number of calls of function block (BASE=FALSE).
- **PERIOD or CYCLES:** Defines the corresponding cycle period.
- **AMPLITUDE:** Defines the amplitude of the function to be generated.



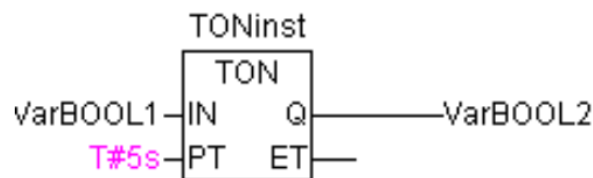
- The function generator is again set to 0 if RESET=TRUE

The output of this function will be a WORD because the Wago output module only accepts variables which are WORD.

The *WAGO Ethernet Setting* program is installed in order to be able to connect the laptop with the PLC. Also the CoDeSys V2.3 is installed in order to program algorithms for the WAGO PLC.

In the program three coils have to be programmed with the sinusoidal wave because there are three coils to control but each of it has to have a different phase. In order to achieve it, what is done in the program is to set two different timers on delay (*TON*) and they will be used as a condition to activate the generation of the sinusoidal wave.

The function block Timer On Delay implements a turn-on delay.



**Figure 11. Example of TON.**

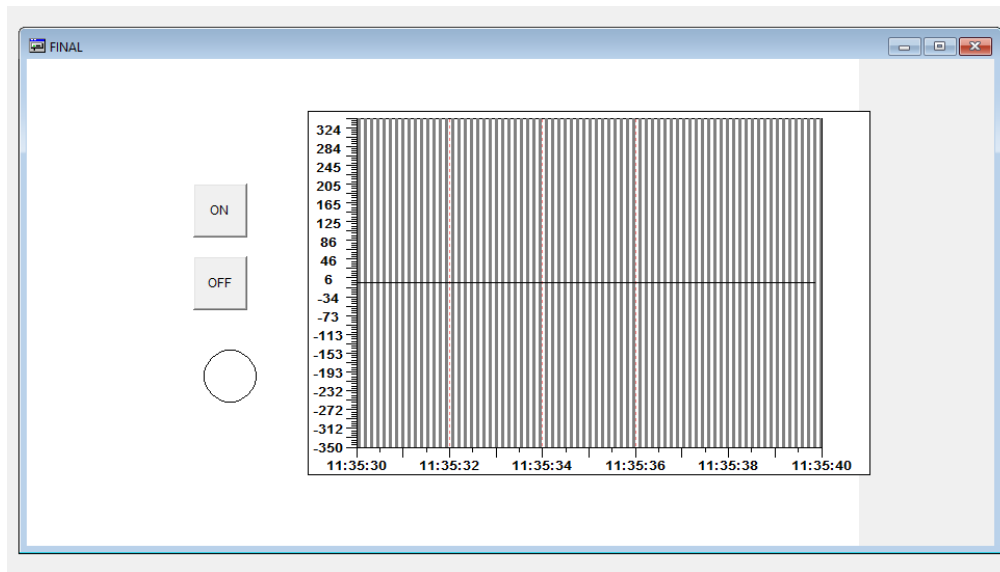
IN and PT are input variables of the BOOL and TIME types respectively. Q and ET are output variables of the BOOL and TIME types respectively. When IN is FALSE, Q is FALSE and ET is 0. As soon as IN becomes TRUE, the time will start to be counted in milliseconds in ET variable until its value is equal to PT. Then it will remain constant.

Q is True if IN is TRUE and ET is equal to PT, otherwise it is FALSE.

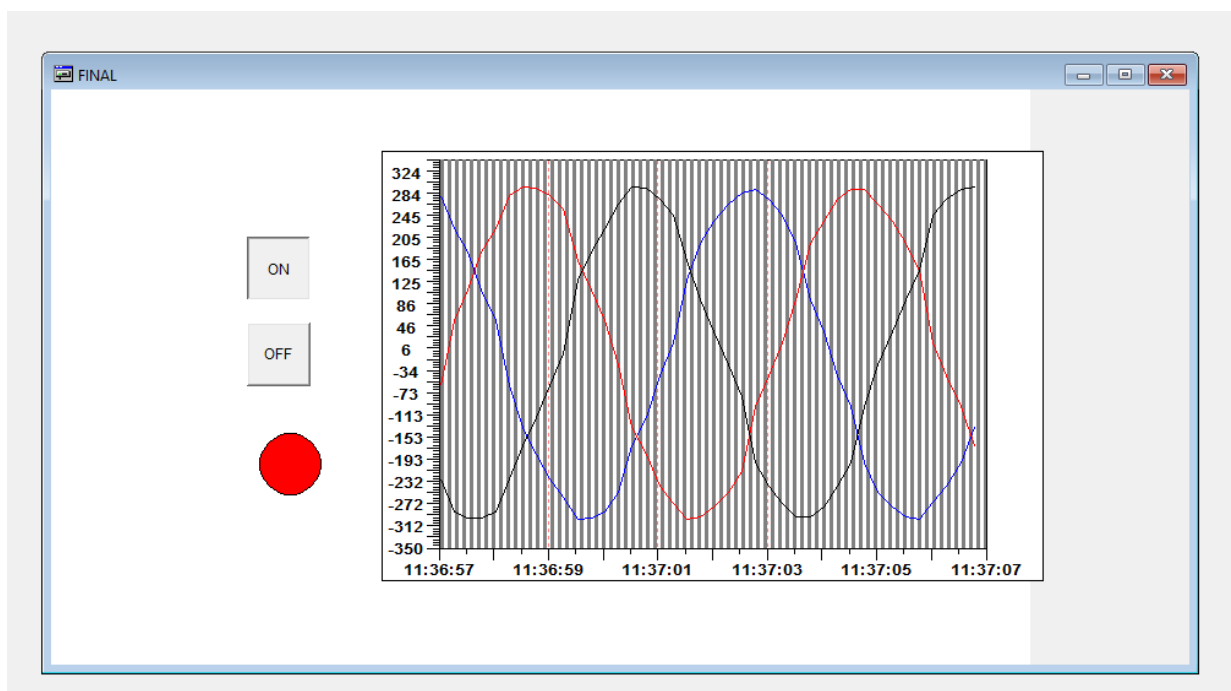
In the program the output variables obtained from the *Gen* function is a WORD and in order to observe better the sinusoidal wave the variables are converted to INT with the function *WORD\_TO\_INT* in order to observe well the negative values of the sinusoid.

#### **4.3.2.1. Interface**

Also an interface is designed to make easier the activation and deactivation of the program. Also the three sinusoidal waves with different phases can be observed.



**Figure 12.** Interface if the program is running but it has not been activated.



**Figure 13.** Interface when the program is in Running mode and it has been activated by pressing the button ON.  
The three sinusoidal waves can be observed

So the output of the program is three sinusoidal waves  $\pm 10$  V following the specifications of the WAGO 750-556 2-Channel Analog Output  $\pm 10$  VDC

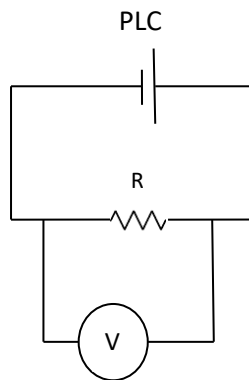
#### 4.3.3. Tests

This program worked perfectly if *Simulation Mode* was used but it gave an error if trying to run it with the PLC and the modules. The error was the following:

### Error 3125: Expression too complex. Use intermediate results

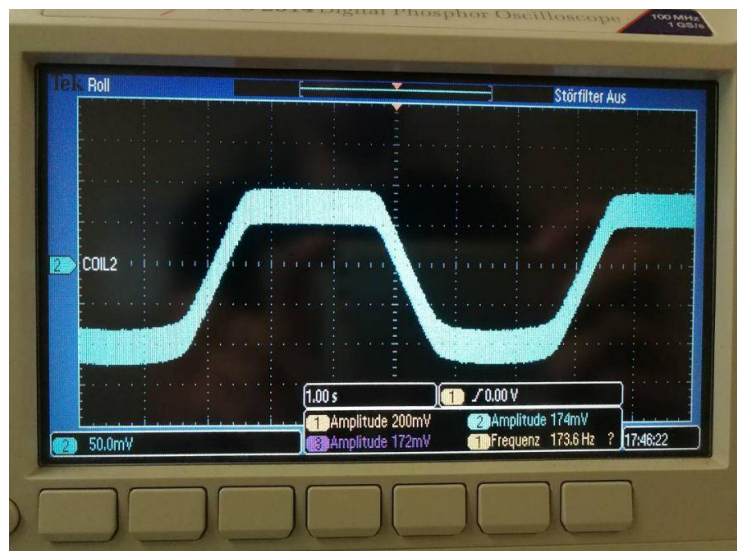
This error was not in the error list of the PLC 750 8202 Manual, neither in CoDeSys one. So the WAGO technical support was contacted in order to solve it. The problem was that all the LREAL variables had to be treated as REAL because the 750-8202 controllers do not support LREAL variables.

The CoDeSys program was tested on the following circuit in order to check how the PLC Output with the following circuit was.



**Figure 14. Electrical circuit test.**

Where  $R = 10 \, \Omega$  so the Volts measured in the oscilloscope will also give the information of the current because of the Ohm's law ( $V=R \cdot I$ ). The output voltage measured by the oscilloscope is the following:



**Figure 15. Output PLC voltage saturated.**

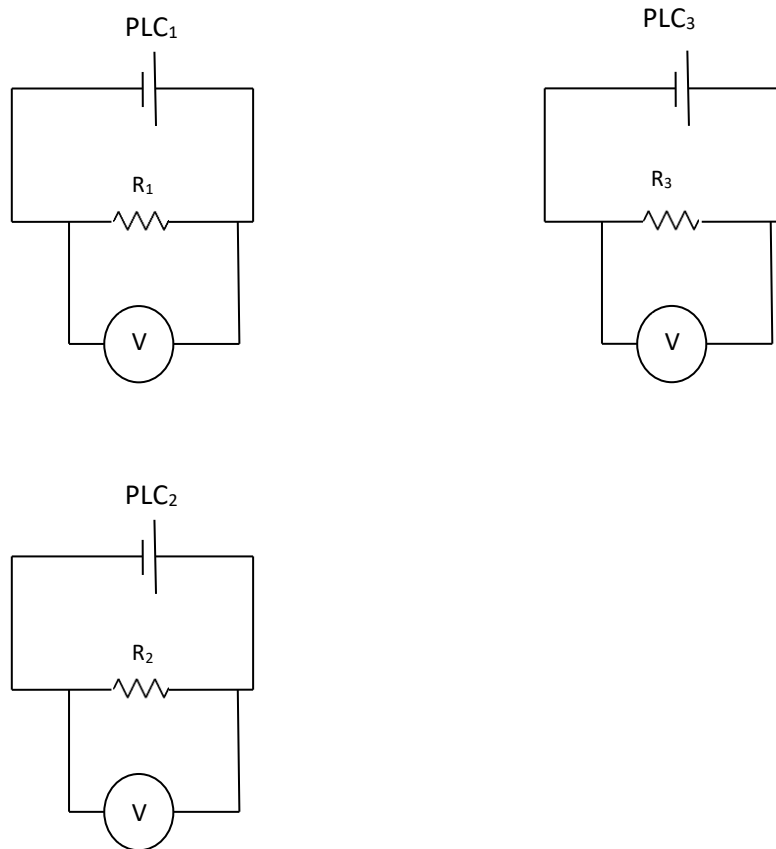
The amplitude measured is 175 mV and because of  $R=10 \, \Omega$ , can be deduced that the current is 1.75 A. It is saturated.

The amplitude is controlled by the *Gen* function generation. In this case the value is 700 in the CoDeSys program that is the reason why the sinusoidal wave is saturated. Trying different values of amplitude with the same electric circuit, it is concluded that the highest value in the CoDeSys program that is not saturated is 300.

The frequency is also controlled from the CoDeSys Program in the *Gen* function generation by setting the period, which is the inverse of the frequency. In this case the period was fixed to 6 seconds so the frequency was:

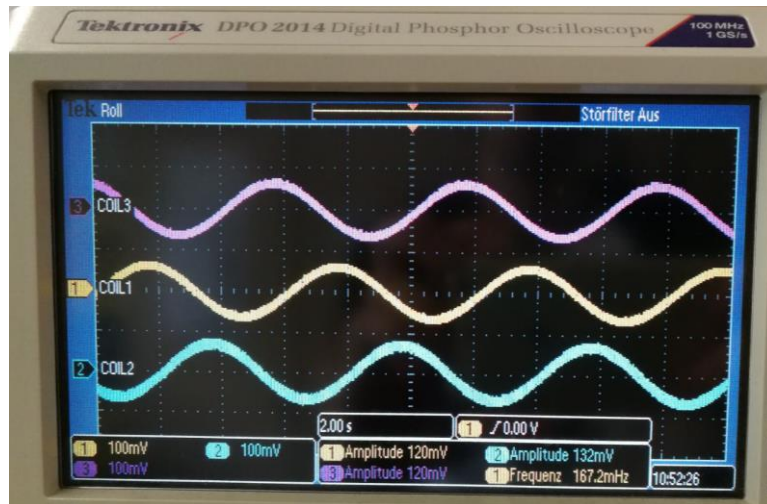
$$Freq. = \frac{1}{6s} = 0.167 \text{ Hz} = 167 \text{ mHz}.$$

The three output channels are checked with the followings circuits:



**Figure 16. Output electrical circuits**

Where  $R_1 = R_2 = R_3$  has the value of  $10 \Omega$  and the voltmeters used are three different channels of the oscilloscope. The voltage measured in the oscilloscope is in the following figure:



**Figure 17. Three sinusoidal waves output with different phases with a frequency of 167 mHz.**

The frequency is still 0.167 Hz. because the period is 6 seconds and the value is about 125 mV. It has decreased comparing to the output obtained in *Figure 23* because the value written in the software program is 300 instead of 700.

The different phases can be observed in the *Figure 24* each period has 6 seconds and each sinusoidal wave has 2 seconds of delay from the previous wave. So the three waves are differenced by  $120^\circ$  of the phase.

#### 4.3.4. Results and conclusions

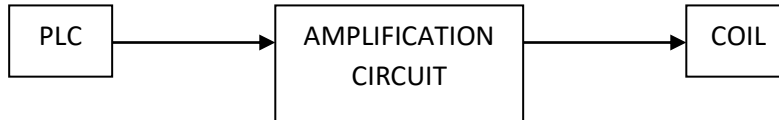
The CoDeSys programming for this part of the project has been much more complex than it was expected. First of all, the working and dynamics of the software had to be learned, to do this implied some time. The process of the design of the program was totally autodidact, so this means that in almost every little step some difficulties were found.

At the end, the program has been well designed and it gives the three sine wave output expected.

## 4.4. Amplification circuit

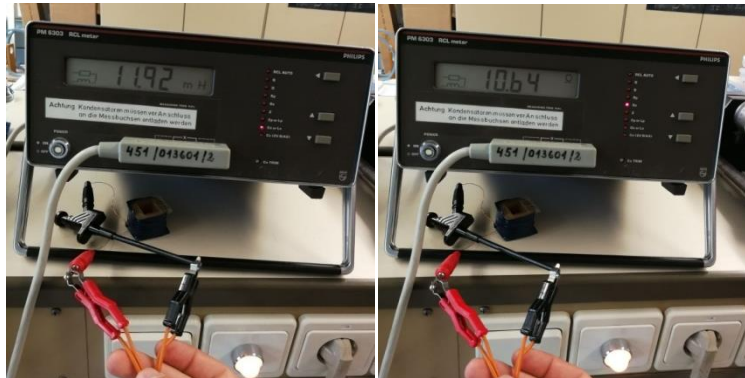
### 4.4.1. Introduction

Due to the fact that the PLC output current is not enough, an amplification circuit is needed because the coils need a current from 0 to 2 Amperes to work in good conditions and to generate enough magnetic fields to close the magneto-active polymer tube, because the tube is normally open.



### 4.4.2. Development

First of all, the inductance and the resistance of the coil are measured with a PM 6303 RLC meter.



**Figure 18. Measurement of the inductance (left) and the resistance (right) of the coil.**

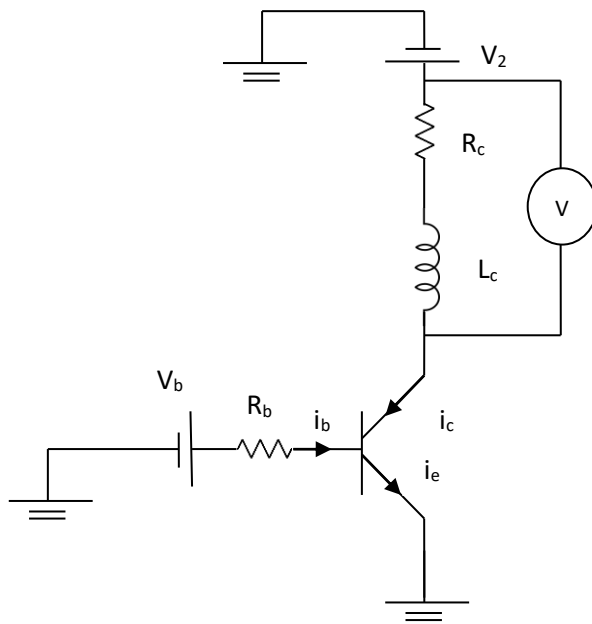
The measured inductance is equal to  $L_c = 12 \text{ mH}$  and the measured resistance is  $R_c = 11 \Omega$ . So the circuit designed for the amplification uses a NPN transistor with a power supply.

First the circuit is tested with a function generator *Agilent 321GA* instead of the PLC. In this function generator the frequency and the voltage amplitude are controlled. The frequency is set to 1 Hz of 10 V<sub>p</sub>.

To simulate the PLC a  $i_b$  current about 20 mA and  $V_b$  of 10 V. With the function generator the current cannot be controlled so to get a current of mA, what can be modified is the  $R_b$ . With the expression (1) can be deduced:

$$R_b = \frac{V_b - V_{be}}{i_b} = \frac{10 - 0,7}{20 \cdot 10^{-3}} = 465 \Omega$$

Due to the fact that the NPN transistor has a specific gain ( $\beta$ ) depending on the  $i_b$ , the  $i_b$  will be incremented by decreasing the value of  $R_b$  because of *Ohm's law* ( $V=R \cdot I$ ) if the  $V_b$  is fixed.



$$V_2 = 24 \text{ V}$$

$$R_c = 11 \Omega$$

$$L_c = 12 \text{ mH}$$

$$R_b = 100 \Omega$$

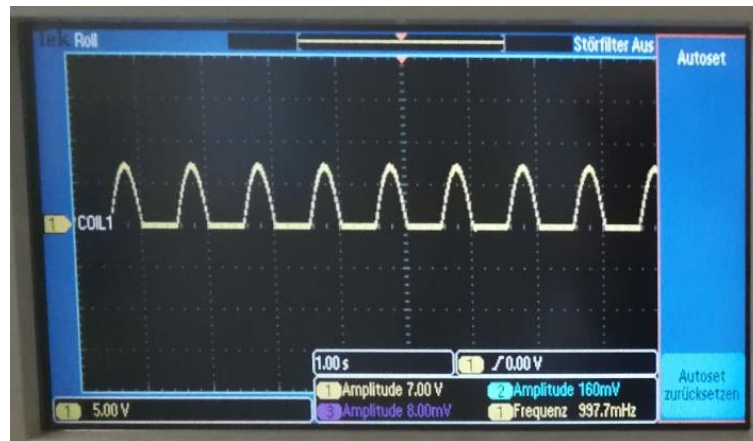
$$V_b = 10 \text{ V}$$

$$i_b = \frac{V_b - V_{be}}{R_b} \quad (1)$$

$$\beta = \frac{i_c}{i_b} \quad (2)$$

$$i_c + i_b = i_e \quad (3)$$

With the Oscilloscope the voltage drop in the coil is measured and the signal obtained can be observed in the following picture.



**Figure 26. Voltage drop in the coil.**

As can be observed in the previous figure the voltage drop in the coil is 7 VDC and it is half sinusoidal wave cut because the transistor between the *collector* and the *base* acts like a diode that amplifies the current. So when the current is positive in the base, it goes amplified to the collector. When the current is negative, the transistor acts like an open switch between the *base* and the *collector*. When there is current in the *collector* of the transistor it means that there is a current through the coil ( $R_c$  and  $L_c$ ). So the coil is activated and the magnetic field

generated to the coil makes a magnetic field against the field of the magnets (NdBFe) which is negated so the MAP tube opens.

In this test the frequency is set to 1 Hz but it also works for different values of the frequency like 0.5 Hz. or 2 Hz.

The amplitude of the voltage drop in the coil is 7 V and knowing that  $R_c = 11 \Omega$  by the Ohm's law the  $i_c$  can be calculated.

$$I_c = \frac{V_c}{R_c} = \frac{7}{11} = 0.64 \text{ A}$$

Expression (1) is used to calculate the base current ( $i_b$ ):

$$i_b = \frac{V_b - V_{be}}{R_b} = \frac{10 - 0.7}{100} = 0.093 \text{ A.}$$

Expresion (2) is used to calculate the gain ( $\beta$ ):

$$\beta = \frac{i_c}{i_b} = \frac{0.64}{0.093} \approx 7$$

The same circuit was tested but with lower  $R_b$  so the  $i_b$  was increased (Ohm's law) so the  $i_c$  was also increased (expression 2). If the  $i_c$  is increased, then the S2000N transistor was highly heated because the collector power dissipation has a value of  $P_c = 50 \text{ W}$ . And if a current of 2 A is set in the collector with a resistance of  $11 \Omega$  the power will be:

$$P_c = I_c^2 \cdot R_c = 2^2 \cdot 11 = 44 \text{ W}$$

The value of 44 W is too close to the collector power dissipation (50 W) so another transistor is used in order to avoid that the transistor is heated. The transistor used is the 2N3055 because the power dissipation is 115 W so it can work in good conditions in the amplification circuit designed.

#### 4.4.3. Results

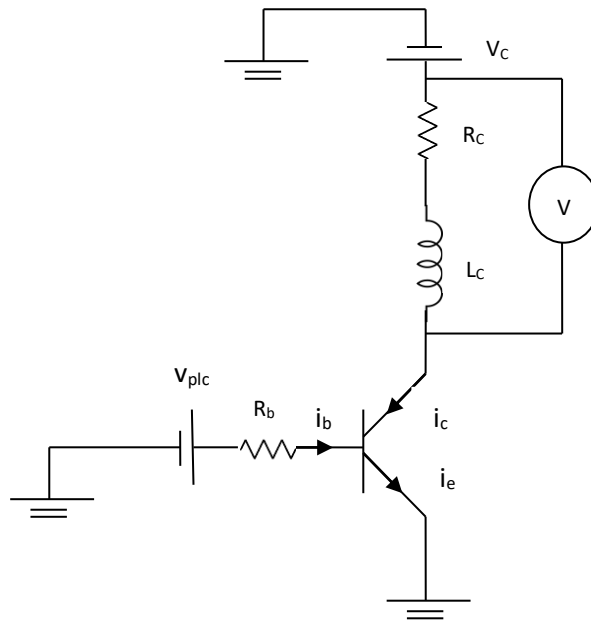
The transistor circuit with the 2N3055 is tested and it works perfectly because it is also an NPN transistor and it uses the same principle. It is preferable the 2N3055 option because the transistor works in better conditions and does not get that warm. The amplification of the current is well fulfilled.

### 4.5. PLC output amplified

#### 4.5.1. Output amplified of one PLC



The amplification circuit is the same as in 4.4. *Amplification circuit* but instead of the S2000N transistor, the 2N3055 is used and instead of a function generator now the Wago PLC is used.



**Figure 19. Amplification electrical circuit.**

$$V_c = 24 \text{ V}$$

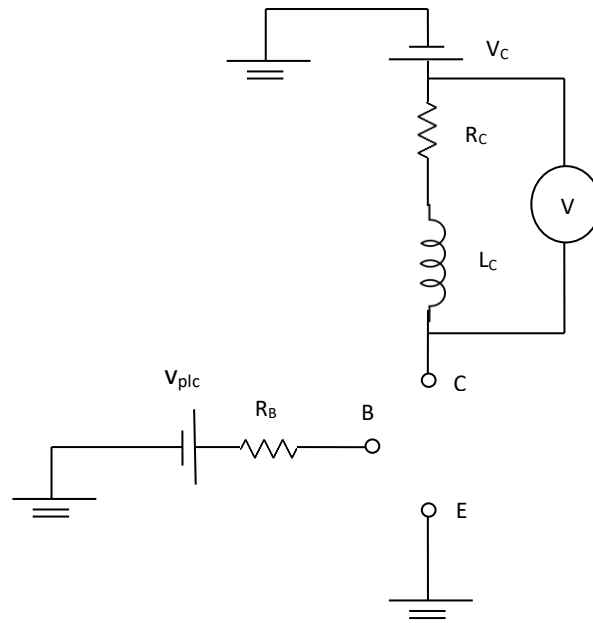
$$R_c = 11 \, \Omega$$

$$L_c = 12 \text{ mH}$$

$$V_{plc} = 10 \text{ V}$$

$$R_b = 10 \, \Omega$$

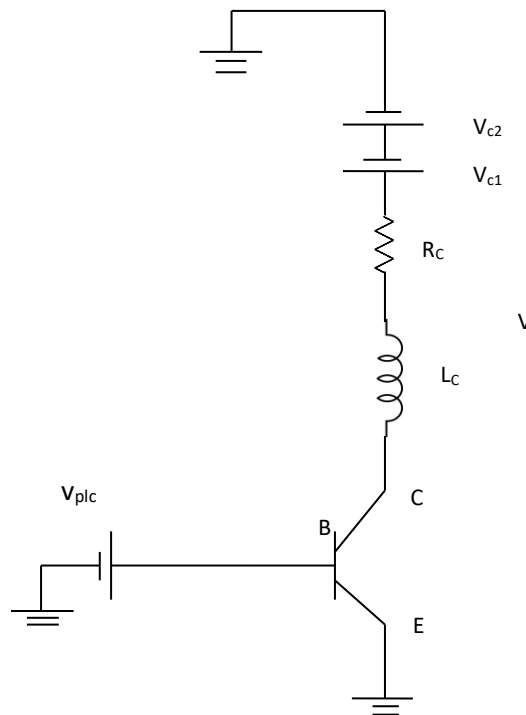
When this circuit was tested no voltage drop was detected in the coil, so no current was going through it. This was because the voltage between the base and the emitter was too low, almost 0 ( $V_{BE} < 0.5 \text{ V}$ ). So it's in cut-off operation mode. It means that the transistor is acting as an open circuit:



**Figure 20. Cut-off operation mode.**

So to solve this problem, by incrementing the voltage in the base the  $R_b$  is removed so the PLC output is directly connected to the base of the transistor. Now the voltage in the base is 10 V, ( $V_{BE} > 0.5$  V) so it means that the transistor is in the active mode.

To achieve the two Amperes in the coil, a higher voltage in the collector is needed. So two power supply of 30 V are connected in series. The total voltage is the sum of the two power supplies. The final circuit is the following one:



**Figure 21. Two power supplies in series are set in the collector.**

$$V_{c1} = 30 \text{ V}$$

$$V_{c1} = 30 \text{ V}$$

$$R_c = 11 \Omega$$

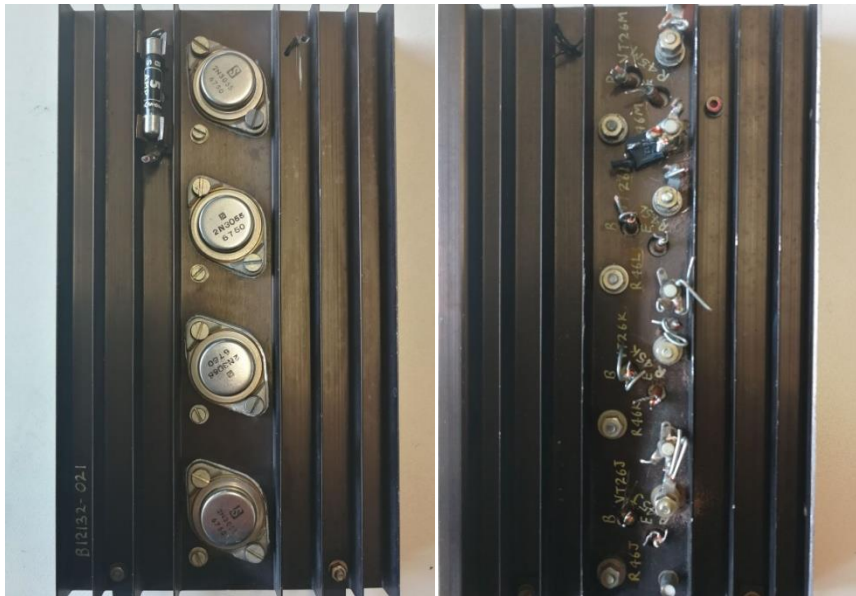
$$V_{plc} = 10 \text{ V}$$

$$L_c = 12 \text{ Mh}$$

The results were the expected ones. A current of 2 A goes through the coil. When the good working of the circuit is confirmed, the same one is prepared three times for the three different phases.

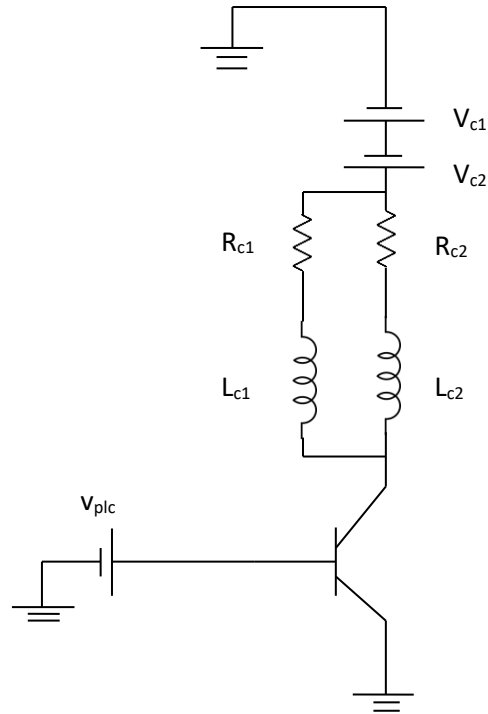
#### 4.5.2. Three outputs with different phases

Actually each phase needs two coils in parallel, not just one as in the previous circuits. Six coils, three 2N3055 transistors and six 30 V power supplies are needed. The three transistors are fixed in the same block as can be observed in the following figure. There are 4, instead of 3 because one of them had leakage current so it was not useful and the other three are the ones used.



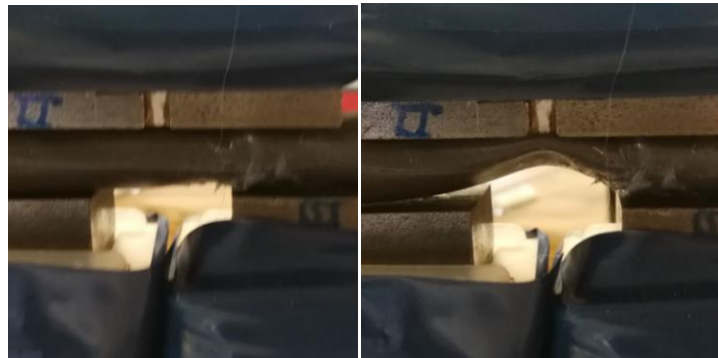
**Figure 22. The case of the four 2N3055 transistors (left) and the connections of the same transistors (right).**

The circuit set for each pair of coils, where each pair of coils has its own phase, is the following:



**Figure 23.** Circuit for each pair of coils.

The result is the correct and the expected one. In the following figure we can see the tube constriction.



**Figure 24.** No current through the coil while the tube is open (left) and 2 A through the coils while the tube is closed (right).

## 4.6. Conclusions

Even though it works well another way using another effect will be used to feed the tube with a sinusoidal magnetic field because now a too high voltage is needed and it is not very efficient.

## 5. PULSE RATE MODULATION EFFECT

### 5.1. Introduction

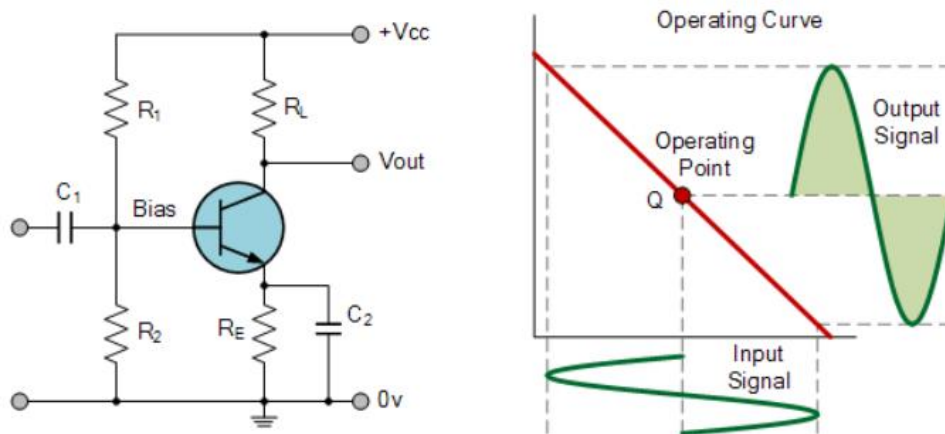
The previous PLC (with the respective CoDeSys program) and the amplification current circuit worked and fulfilled the goal set at the beginning. A 2 A current passed through each pair of coils. But it was not really efficient; a high voltage was needed to achieve the desired current. To drive the coils with an analog sinewave requires a Class-B amplifier. Class-B amplifiers have a maximum efficiency of 25% which is why twice the voltage and twice the current were required to achieve the desired current through the coils. This made the transistors get rather warm. So the same goal will be fulfilled but this time in a more efficient way.

### 5.2. Amplifiers classification

#### 5.2.1. Class A amplifiers

This type is the most used one due to its simple design. It has low distortion levels. It has the highest linearity and it operates in the linear portion of the characteristics curve. Generally it is a single transistor such as Bipolar, FET, IGTB, etc. The transistor is connected to a common emitter configuration for both halves of the waveform. It has always signal through it, even if there is no current in the base. This means that the transistor is always working in the active region and it is never driven to the cut-off or saturation region. Because of that, the single output device conducts through a full 360 degrees of the output waveform.

The transistor never turns OFF, which can be a disadvantage because the output device is “ON” at all times, it is constantly carrying current, which represents a continuous loss of power in the amplifier. It has efficiency around 25%. The device gets too heat, so it is not useful for high-power amplifications.



**Figure 25.** Class A amplification circuit example and Class A operating curve with the input and output signals.

### 5.2.2. Class B amplifiers

These amplifiers are more efficient and they are less heated. Two complementary bipolar or FET transistors for each half of the waveform are used, so that each transistor amplifies only half of the output waveform. There is no DC base bias current.

If the input signal goes positive, the positive biased transistor conducts and the negative transistor is switched “OFF”. If the input signal goes negative, the positive transistor switches “OFF” and the negative biased transistor switches “ON”. Thus the transistor conducts only half of the time, either on positive or negative half cycle of the input signal.

Each transistor device of the class B amplifier only conducts through 180 degrees of the output waveform. But as the output stage has devices for both halves of the signal waveform the two halves are added together to produce the full linear output waveform.

The efficiency is much higher than class A, it is around 50%, but the problem is that it can create distortion at the zero. The transistors have a base-emitter voltage of about 0.7 V to start conducting. Then the transistor is not ON until this voltage is exceeded.

This means that the part of the waveform which falls within this 0.7 volt window will not be reproduced accurately. To fix this problem, exists the class AB amplifier.

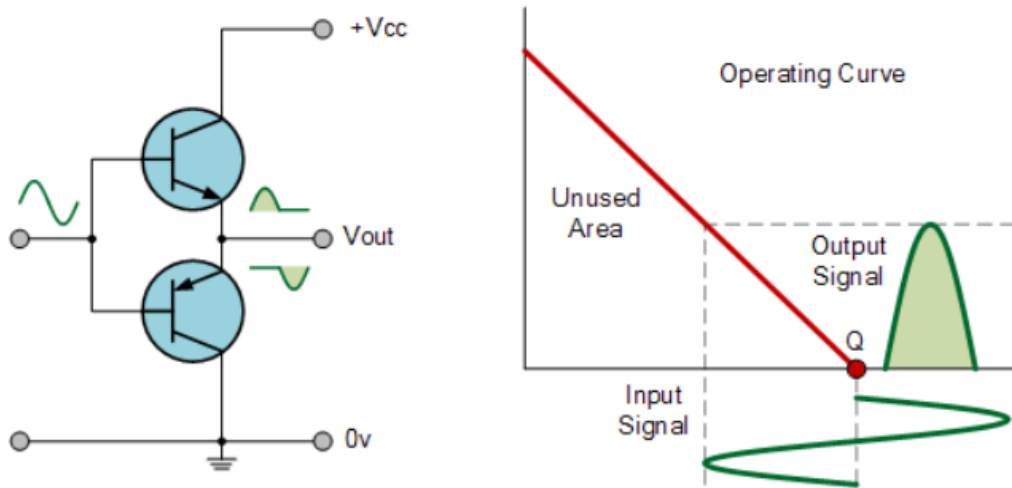


Figure 26. Class B amplification circuit example and Class B operating curve with the input and output signals.

### 5.2.3. Class AB amplifiers

It is a combination of the Class A and B. It also has two transistors but both devices conduct simultaneously around the waveforms crossover point eliminating the distortion problems of the class B amplifier.

Both transistors have a very small bias voltage, typically at 5% to 10% of the quiescent current to bias the transistors just above its cut-off point. The conducting device, either bipolar or FET, will be ON, for a bit more than half cycle.

Efficiency is about 50% to 60%.

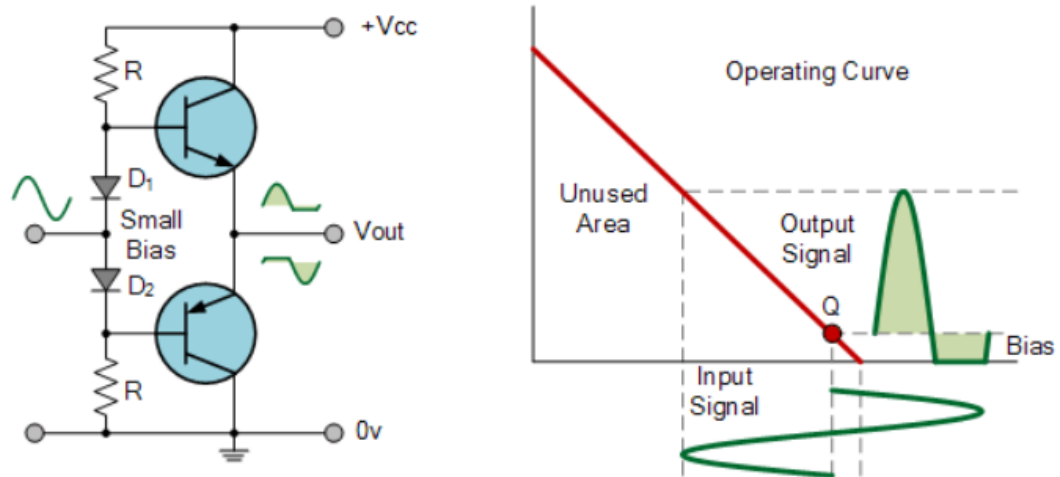


Figure 27. Class AB amplification circuit example and Class AB operating curve with the input and output signals.

#### 5.2.4. Class C amplifiers

The output signal flows during less than half of the cycle of the input. It works for a narrow frequency bandwidth in high frequencies where the pulses of the current produced at the amplifiers output can be converted to complete sine waves of a particular frequency with LC resonant circuits in the collector.

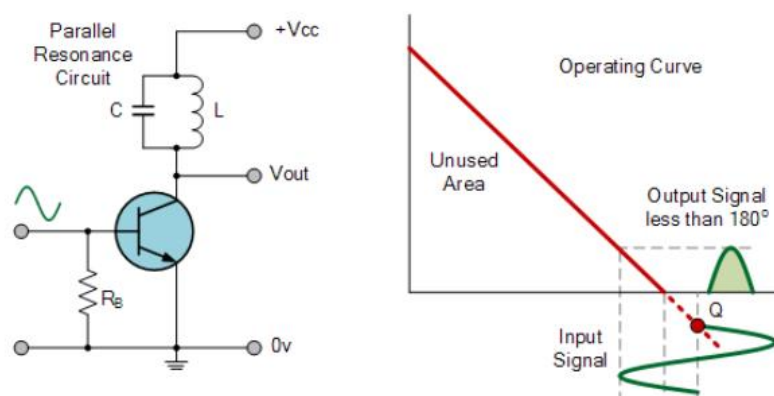


Figure 28. Class C amplifiers circuit and class C operating curve.

### 5.2.5. Class D amplifiers

#### 5.2.5.1. Definition

It is a non-linear switching amplifier using pulse width modulation (PWM) technique. It can theoretically reach 100% efficiency because there is no period during a cycle in which the voltage and current waveforms overlap as current is drawn only through the transistor that is on. The devices work in the cut-off and saturation region, in order to regulate the input power.

#### 5.2.5.2. Pulse-width modulation technique (PWM)

The pulse width modulation (PWM) is a technique in which the working cycle of a periodic signal is modified in order to transmit information through a communication channel or to control the amount of energy that is sent to the charge. It controls the power supplied to electrical devices, such as coils or motors.

The duty cycle is the proportion of ON time to the regular interval period of time.

$$D = \frac{\tau}{T}$$

D: duty cycle

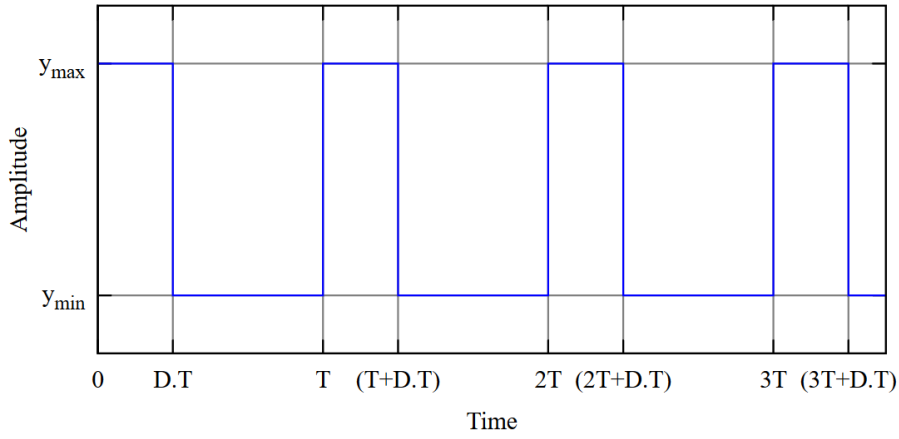
$\tau$ : Time where the switch is ON (pulse-width).

T: Function period of the charge.

The average value of voltage (and current) supplied to the charge is controlled by turning on the switch between supply and load ON and OFF at a fast rate. The longer the switch is ON compared to the OFF periods, the higher the total power supplied to the charge.

PWM uses a rectangular pulse whose width is modulated resulting in the variation of the average value of the waveform  $f(t)$ , with period T, low value  $y_{min}$  and high value  $y_{max}$ , the duty cycle D as shown in the following figure.





**Figure 29. Plot of the pulse signal  $f(t)$ , with the  $y_{max}$ ,  $y_{min}$ ,  $D$  and  $T$  definitions are represented.**

Then the average value is given by:

$$\bar{y} = \frac{1}{T} \int_0^T f(t) dt.$$

As  $f(t)$  is a pulse wave, its value  $y_{max}$  for  $0 < t < D \cdot T$  and  $y_{min}$  for  $D \cdot T < t < T$ . The average value can be expressed as:

$$\begin{aligned} \bar{y} &= \frac{1}{T} \int_0^{D \cdot T} y_{max} + \frac{1}{T} \int_{D \cdot T}^T y_{min} dt = \frac{1}{T} (D \cdot T \cdot y_{max} + T(1 - D)y_{min}) \\ &= D \cdot y_{max} + (1 - D) \cdot y_{min} \end{aligned}$$

If  $y_{min}=0$  the previous expression can be  $\bar{y} = D \cdot y_{max}$

If the duty cycle is low, the power to the load is also low.

The turning ON and OFF the switching frequency is much higher than the one of the charge. The higher the frequency is of the switch, the smoother the signal through the load.

There is almost zero power loss in the switching devices. If the switch is OFF, there is no current and if it is ON and power is transferred to the load, there is almost no voltage drop through the switch. So in both cases there is almost no power loss. The efficiency is almost 100%, thus the project will be done using this technique.

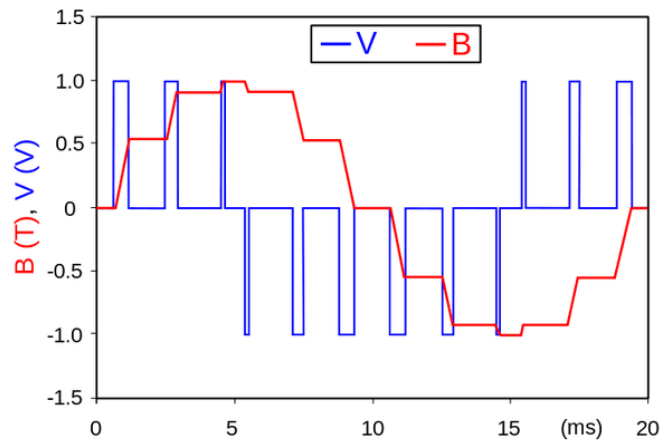


Figure 30. Sinusoidal magnetic field (red) controlled by pulse width modulation technique.

### 5.2.6. Amplifiers classes and efficiency

As mentioned before, the different kinds of amplifiers have different efficiencies and different conduction angles. Each type of amplifier is used for different applications.

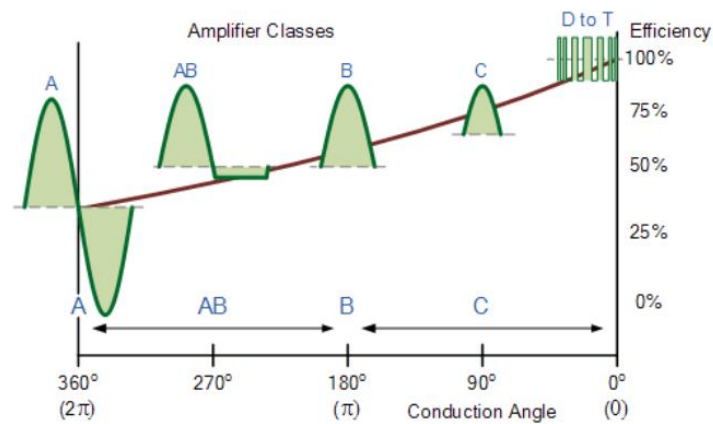


Figure 31. Efficiency (%) vs. Conduction angle (°) with the different classes of the amplifiers.

## 5.3. CoDeSys Program

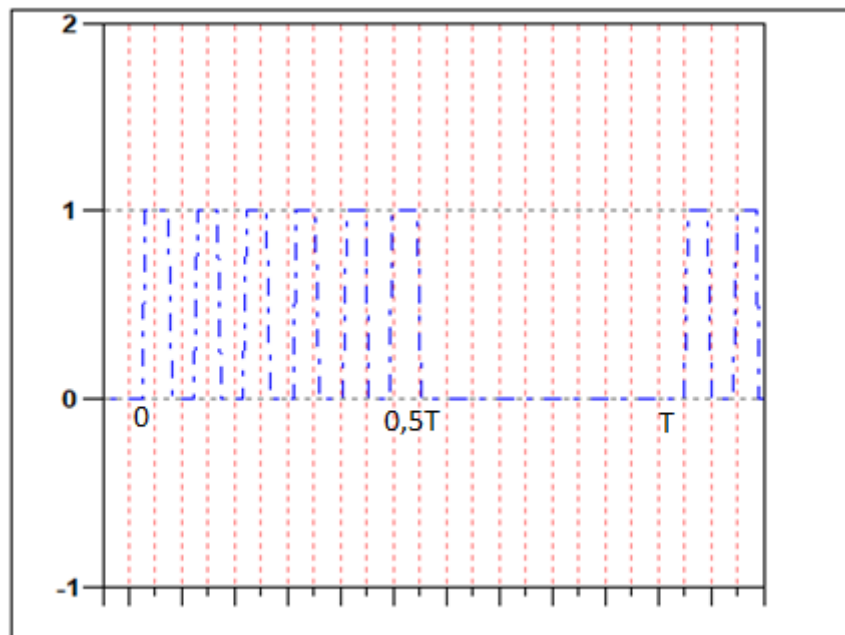
### 5.3.1. Introduction

The Pulse Width Modulation will be used and the coil will be considered as an ideal inductor. A series of pulses will modulate the magnetic field  $B(T)$ . If the pulse signal is positive the magnetic field will rise. If the pulse signal is zero, the magnetic field generated by the coil will

remain constant if considered as an ideal inductor (but will decrease in real inductor) and if the pulse signal is negative the magnetic field will decrease.

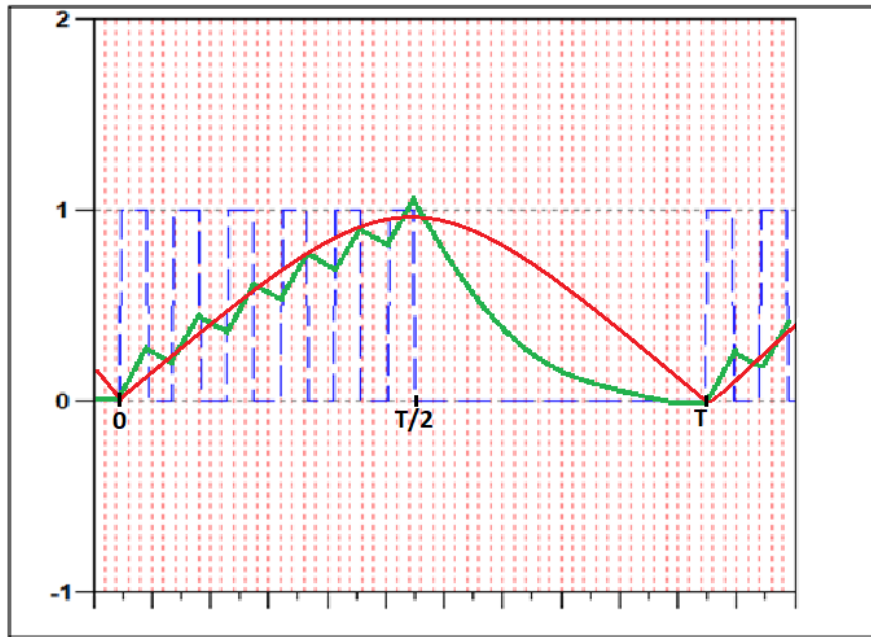
Programing with the CoDeSys V2.3 a pulse wave can be designed controlling the duty cycle and the frequency.

The output of the program is the following. Six pulsed peaks occur during the first half of the period. The length of the peaks and the time between those peaks is the same. During the second half of the current is null.

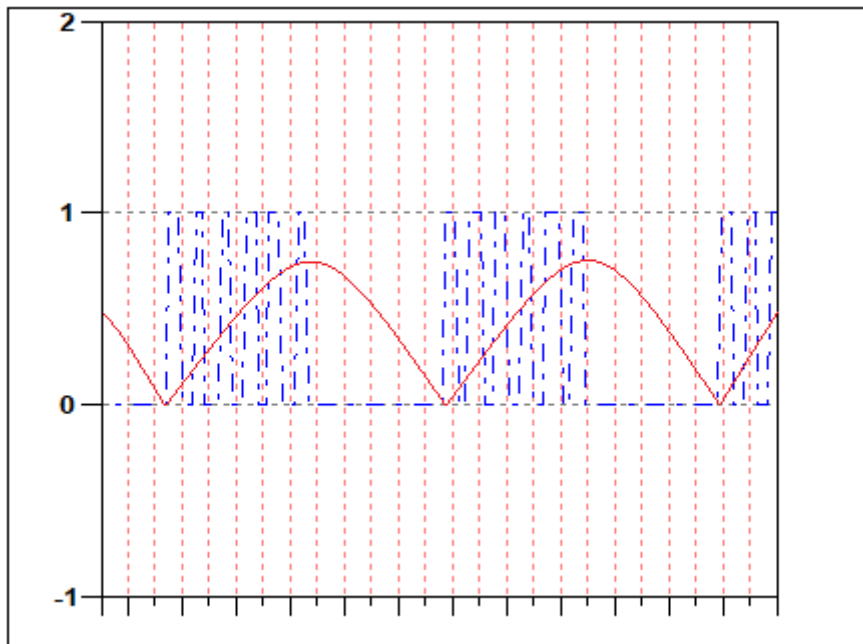


**Figure 32. Output of six pulsed peaks in the first half of the period of the designed Codesys program.**

According to Faraday law, a magnetic field will be generated because of the pulses generated. The magnetic field will have the green form of the following figure which can be approximated as a sinusoidal wave, which can be observed in red color.



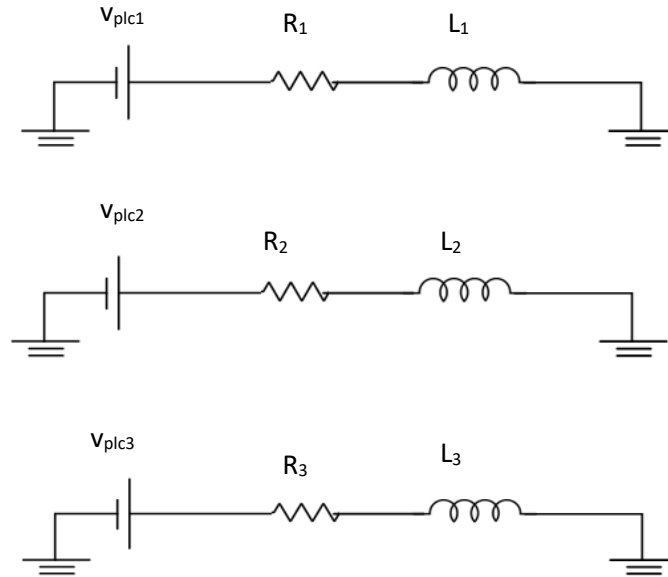
**Figure 33.** Output signal current (blue), magnetic field (green) and sinusoidal magnetic field approximation (red) of one period.



**Figure 34.** Program output with the sinusoidal magnetic field approximation of multiple periods.

### 5.3.2. Development

The Codesys program showed in is tested with a high power resistor in series of the coil for security reasons. If the resistors from the circuit are not high power resistors they will get burned. A  $6\ \Omega$  resistance is set in series with the coil so the circuit tested is the following:



**Figure 35.  $6\ \Omega$  resistance in parallel with each coil.**

Where  $R_1 = R_2 = R_3 = 6\ \Omega$ .

The circuit tested works well, the pulsed current is brought to the coil but it does not make contract as much as wanted the tube. Also when the second coil is started suddenly the PLC switches OFF.

The program is tested again with the circuit but now the PLC power supply is changed because the one that was given predefined can only supply 2 A to a one that holds until 15 A, because when the second coil was activated while the first one was still working, the power supply could not feed two coils at the same time. That is the reason why the power supply is changed.

Also the resistances are left out, because some voltage is left in the resistances and then less voltage is left for the coils. Following Ohm's law, if there is less voltage it means that there is less current.

With these two changes in the circuit, the program is set to 1 Hz of frequency (the period is equal to one second) and the results are the waited ones; it works as expected. As can be seen in the following figures:

It should be also said that because the three coils are separated  $120^\circ$  and only half of the period there is current flowing through the coils there are there are six different phases:

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Coil 1	ON	ON	OFF	OFF	OFF	ON
Coil 2	OFF	ON	ON	ON	OFF	OFF
Coil 3	OFF	OFF	OFF	ON	ON	ON

The first phase only closes the first section so the fluid is squeezed forward.

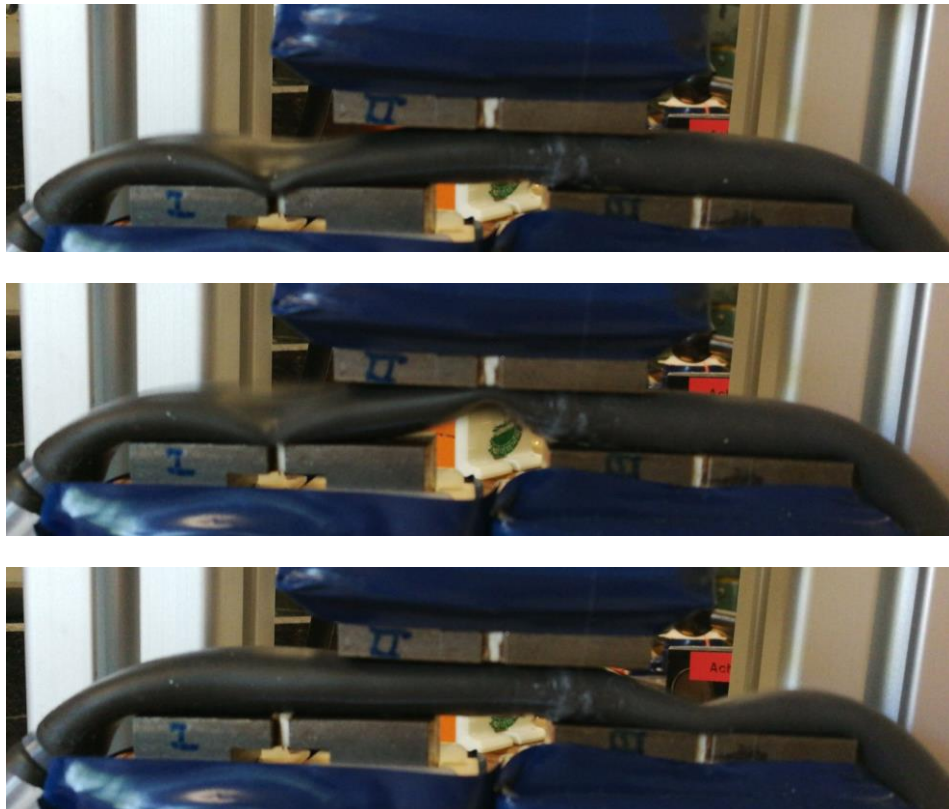
In the second phase first and second one are constricted. A chamber between these two sections is emerged full of fluid.

The third phase is the turning OFF of the section one.

The fourth phase a chamber between section 2 and section 3 is emerged because both sections are switched ON.

The fifth phase releases the chamber between the section 2 and 3 by switching OFF the coil 2, so the tube expands itself.

The sixth phase creates a big chamber between section 1 and section 3 which is released in the first phase.



**Figure 36. Three different phase of the pumping. The first phase is represented at the top, the second phase in the middle and the fifth phase at the bottom.**

## 6. Frequency and pulsed signal type study when working as a water pipe

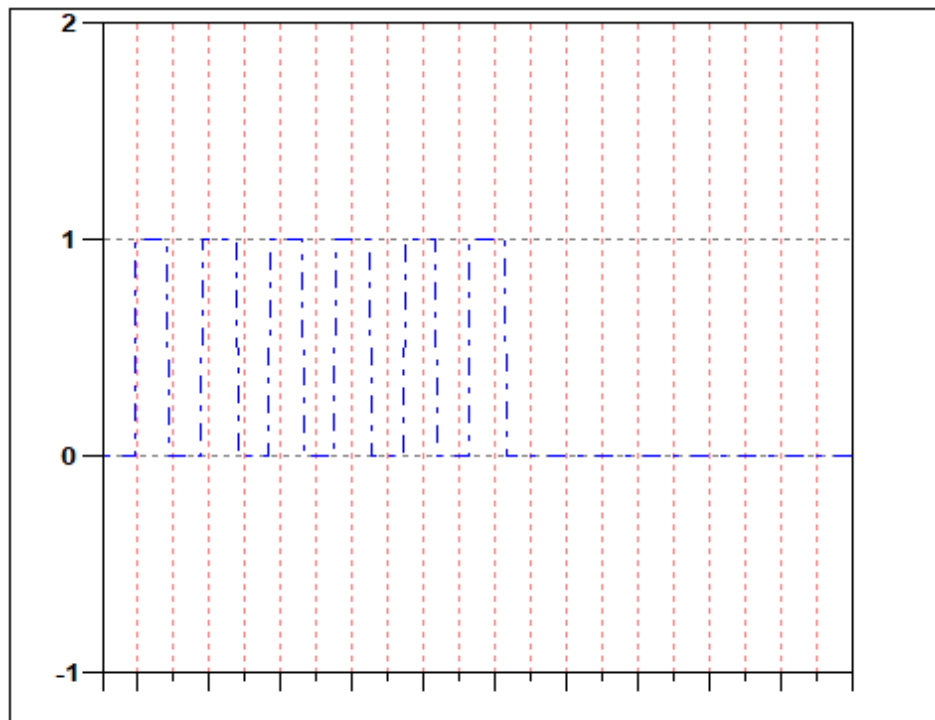
### 6.1. Introduction

The magneto active polymer tube can have multiple applications in different fields of engineering, research and in human daily lives. One of this applications could be that it can work as a fluid pipe using few amount of current because the tube is normally open and only a current pulse of 2 A has to be given to the coils to close the tube. The way and speed of how the tube closes and opens might affect to the movement of the fluid inside.

In this thesis different designed programs changing the kind of pulse wave are tested in order to observe how it affects to the fluid movement. Also multiple frequencies are tested. The results will be analyzed and compared.

### 6.2. Digital Programs designed

#### 6.2.1. Program 1



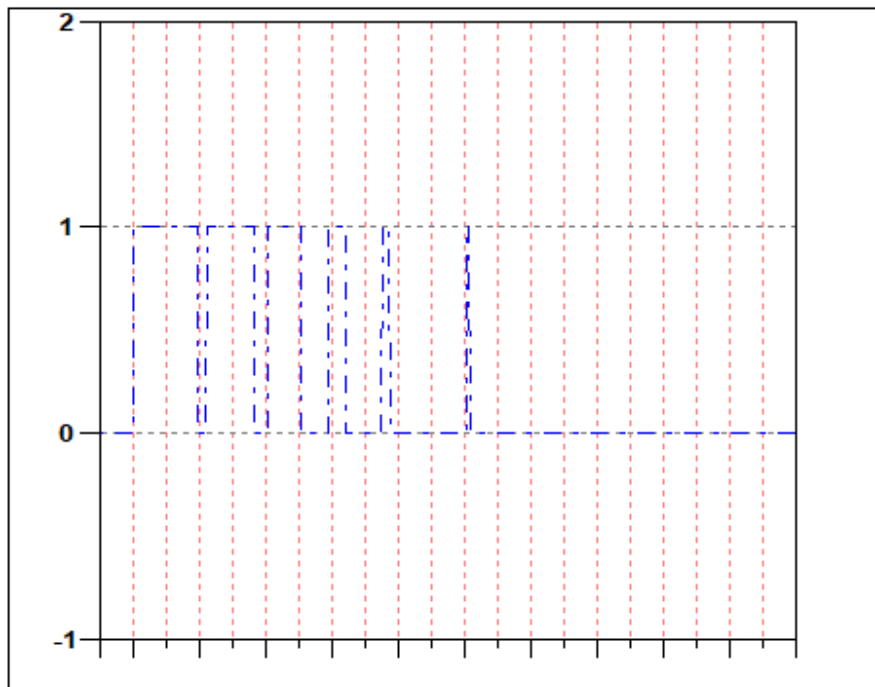
*Figure 37. Program 1 output plot.*

The first program consists of six pulsed peaks in the first half of the period equally separated in time. The time between these six peaks is the same length as the peaks. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM01.pro](#)

### 6.2.2. Program 2



*Figure 38. Program 2 output plot.*

The second program consists of six pulsed peaks in the first half of the period. The first peak is the longest and the length of the peak is decreased through the following peaks. The time length between these six peaks is increased after each peak. The second half of the period there is no current flowing.

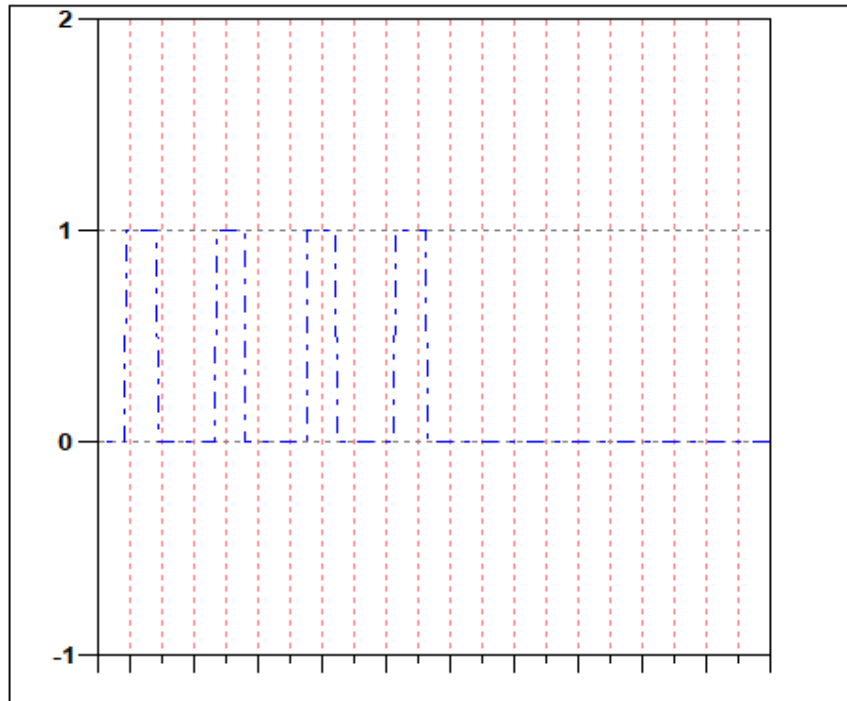
The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM02.pro](#)

.



### 6.2.3. Program 3



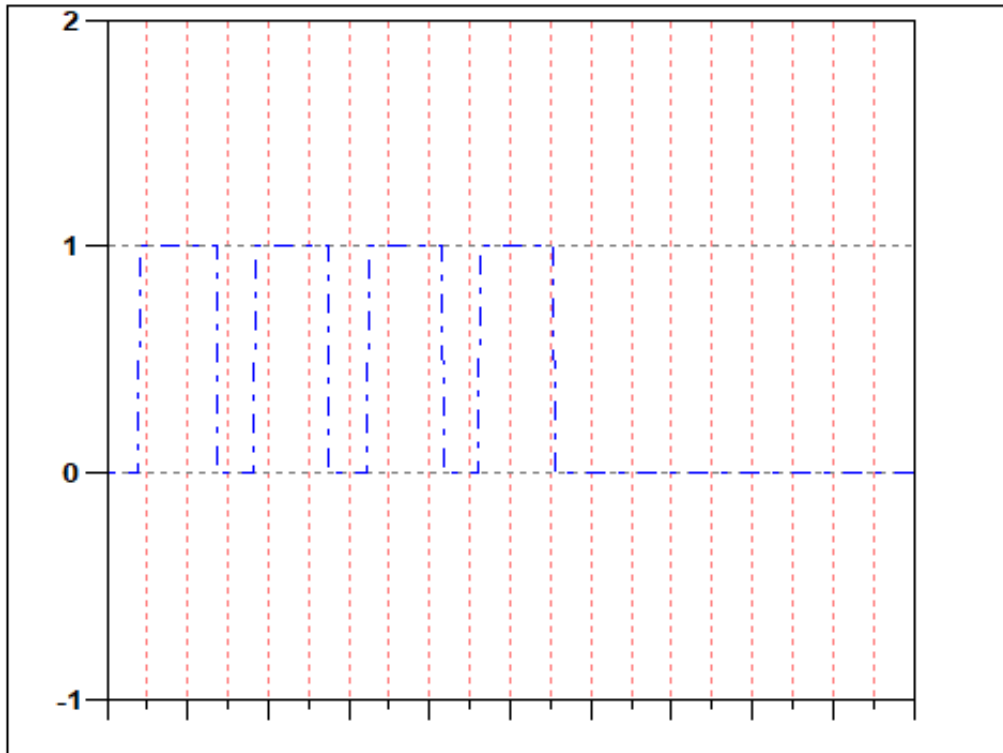
*Figure 47. Program 3 output plot.*

The third program contains four pulsed peaks in the first half of the period. All of them have the same time length and they are equally separated in time. The time between the peaks has the double peak's length. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorithm of this program can be found in [PROGRAM03.pro](#)

#### 6.2.4. Program 4



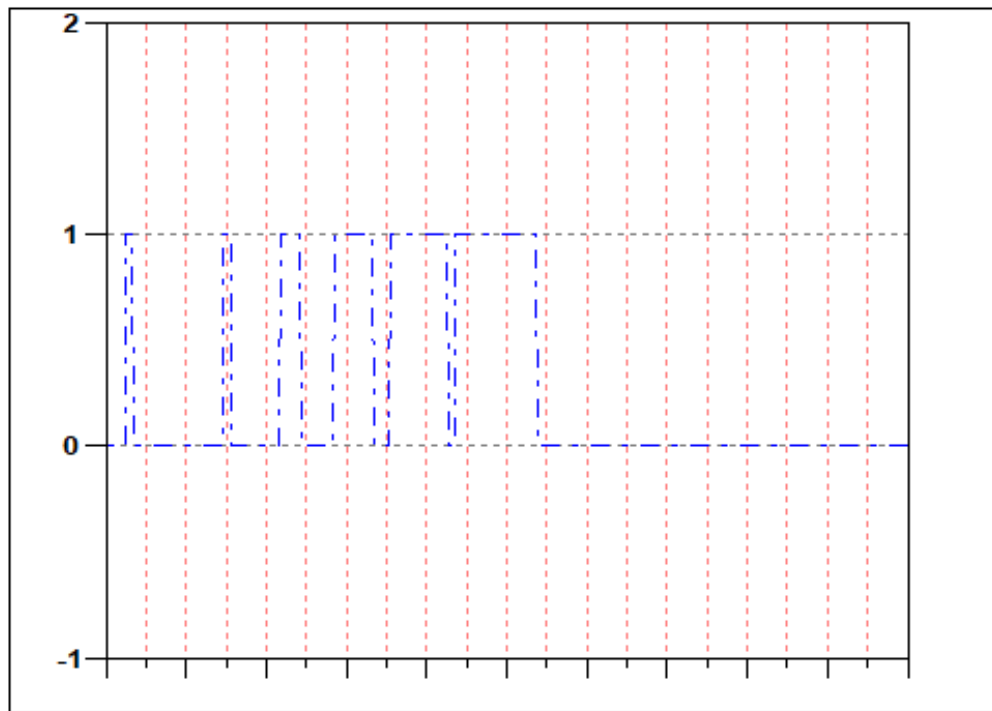
*Figure 39. Program 4 output plot.*

The fourth program contains four pulsed peaks in the first half of the period. All of them have the same time length and they are equally separated in time. The time between the peaks has the half of the peak's length. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorithm of this program can be found in [PROGRAM04.pro](#)

#### 6.2.5. Program 5



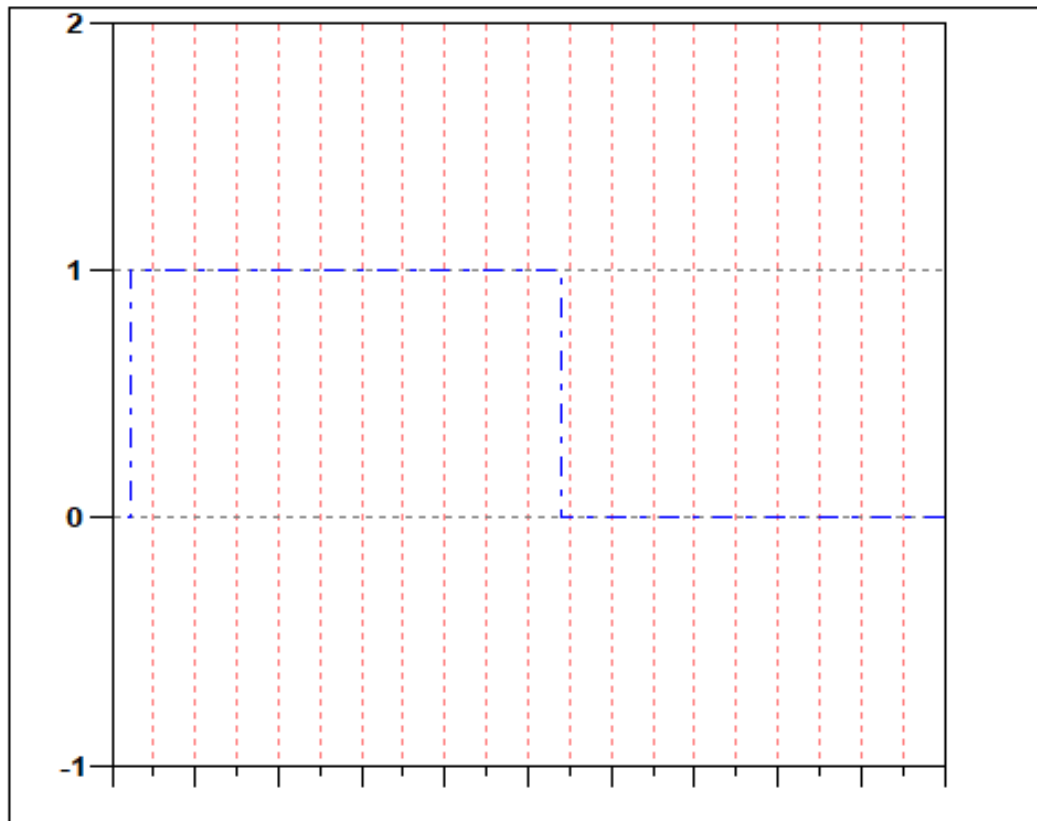
*Figure 40. Program 5 output plot.*

The fifth program consists of six pulsed peaks in the first half of the period. The first peak is the shortest one and the length of the peak is increased in the following peaks. The time length between these six peaks is decreased after each peak. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorithm of this program can be found in [PROGRAM05.pro](#)

### 6.2.6. Program 6



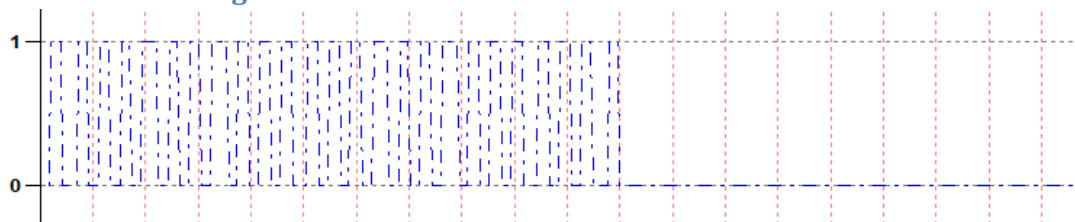
*Figure 41. Program 6 output plot.*

The sixth program consists of the standard pulsed signal. The first half of the current the signal is ON and in the second half of the period there is no current flowing, which means that the signal is OFF.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorithm of this program can be found in [PROGRAM06.pro](#)

### 6.2.7. Program 7

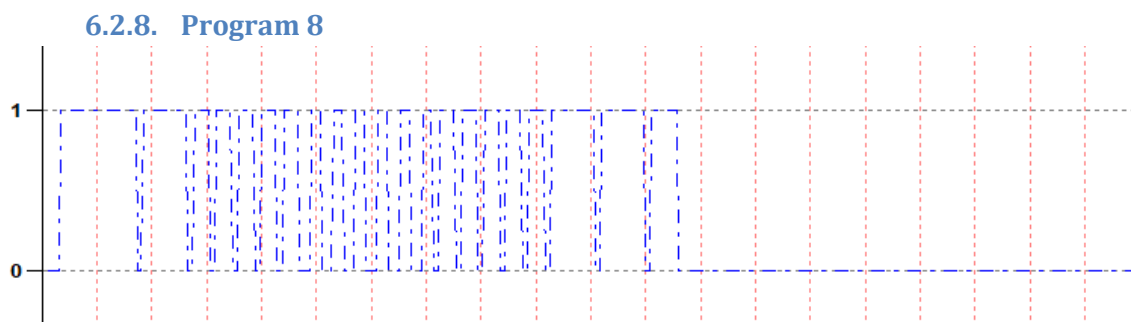


*Figure 42. Program 7 output plot.*

The seventh program consists of 25 pulsed peaks in the first half of the period equally separated in time. The time between each peak has exactly the same length as each peak. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM07.pro](#)

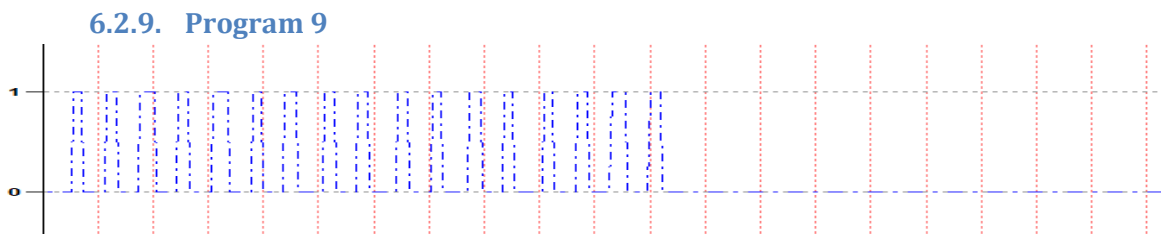


*Figure 43. Program 8 output plot.*

The seventh program consists of six pulsed peaks in the first half of the period equally separated in time. The peaks at the start and at the end of the first half of the period are the longest ones. The space between the peaks is also longer in the middle of the first half of the period.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM08.pro](#)



*Figure 44. Program 9 output plot.*

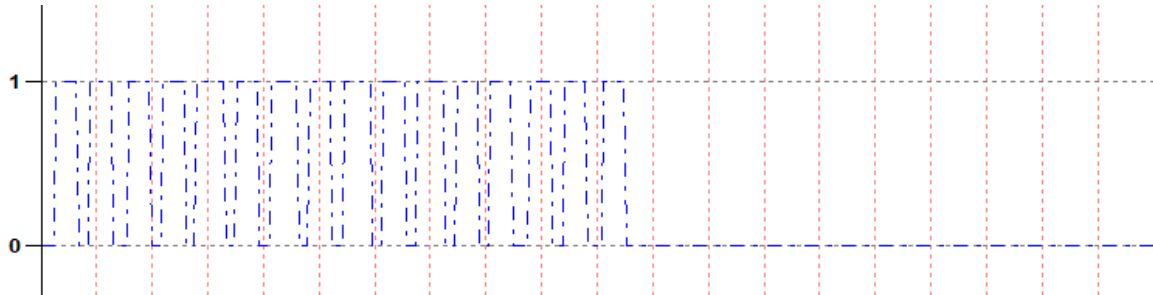
The ninth program contains 17 pulsed peaks in the first half of the period. All of them have the same time length and they are equally separated in time. The time between the peaks has the double peak's length. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM09.pro](#)

.

#### 6.2.10. Program 10



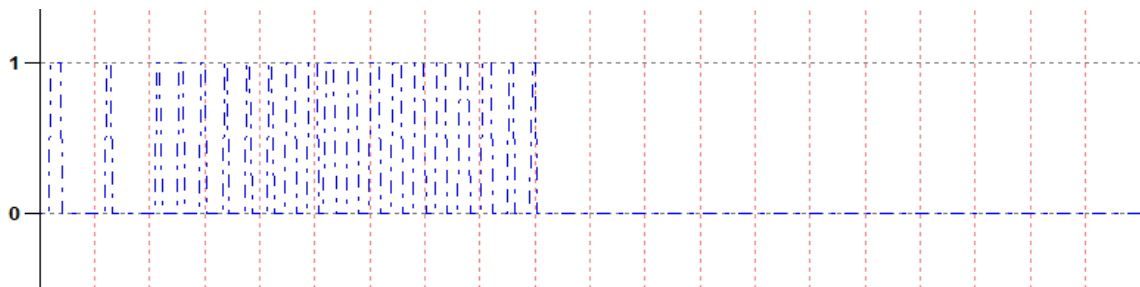
*Figure 45. Program 10 output plot.*

The tenth program contains sixteen pulsed peaks in the first half of the period. All of them have the same time length and they are equally separated in time. The time between the peaks has the half of the peak's length. The second half of the period there is no current flowing.

The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM10.pro](#)

#### 6.2.11. Program 11



*Figure 46. Program 11 output plot.*

The eleventh program consists of twenty pulsed peaks in the first half of the period. The peaks at the start and at the end of the first half of the period are the shortest ones. The space between the peaks is shorter in the middle of the first half of the period.

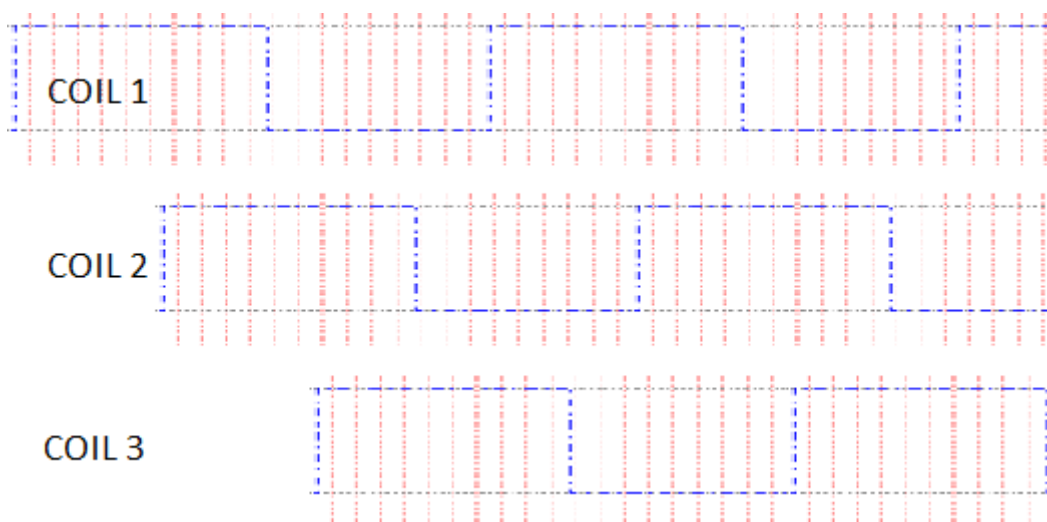
The frequency can be changed and controlled easily through the variables declaration of the program.

The variables and algorism of this program can be found in [PROGRAM11.pro](#)

## 6.3. Tests

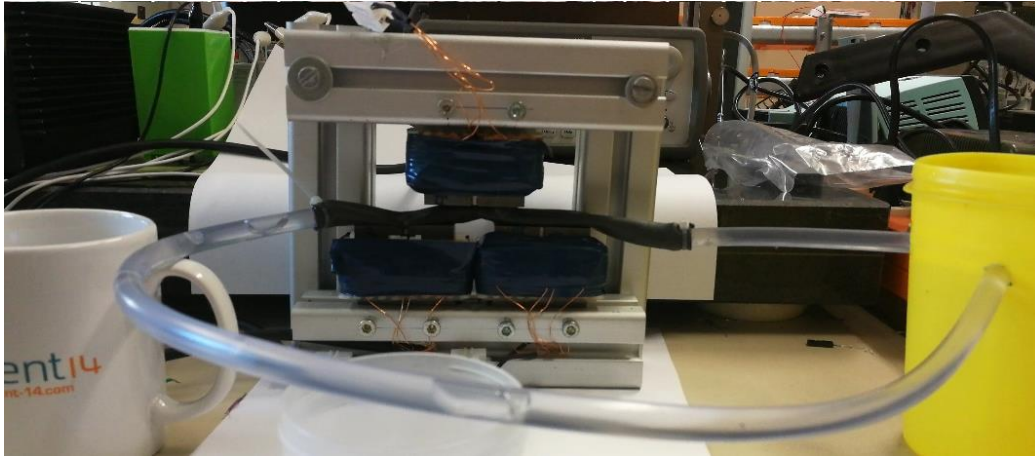
### 6.3.1. Introduction and background

The eleven programs presented in the previous point were used to feed three coils of the magneto-active polymer actuator. Each coil was fed with a separation of  $120^\circ$  of the periodic signal or in other words, being separated of one third of the periode length time. The difference of the phase can be observed in the following figure:



*Figure 47. Difference of phase of program 4.*

When the coils of the tube are fed with current and the tub opens and closes, water is put inside the tube so that the tube acts as a pump. It has to bring water from one deposit to another one at the same height, so there are no changes of potential energy. Also the whole tube is at the same height of both deposits (the initial were water is taken from and the final were the water is pumped to).



**Figure 48. Pumping experiment.**

The tube has an inner diameter of 9 mm, 1.5 mm of wall thickness.

Each signal type was tested in different frequencies; the results are analyzed in different aspects:

- The general movement can be forwards or backwards, if there is movement.
- The period movement can be pulsed or soft. If it is pulsed it means that the movement is stop in every period of the signal. If it is soft it means that the fluid moves without any stops through the tube.
- Within a period the fluid can move forward and also backwards during the period time. If this happens it means that also the movement is pulsed.
- A vibration can appear or not while the tube is pumping.

The videos of the tests can be found in *Annex 9.3*.

### 6.3.2. Results

All this aspects are analyzed in different tables.

The programs 1, 2, 3, 4, 5 and 6 were tested with frequencies of 1 Hz, 2 Hz, and 4 Hz. If the frequencies were faster there would not be 100 % of constriction of the tube.

<b>Program 1</b>	1 Hz frequency	2 Hz frequency	4 Hz frequency
General movement	Forwards	No	No
Soft or pulsed	Pulsed	No	No
Period movement(s)	It does not go back, it only moves forward and stops	No	No
Vibration	Yes	Yes	Yes
Observations	It is between forward movement and vibration.	There is only vibration.	There is only vibration, it is smaller of when 2 Hz



<b>Program 2</b>	1 Hz frequency	2 Hz frequency	4 Hz frequency
General movement	Forwards	Backwards	No
Soft or pulsed	Pulsed	Pulsed	No
Period movement(s)	It goes forwards and then it stops.	It goes backwards a bit and then stops.	No
Vibration	No	No	Yes
Observations	It moves forward well		The tube does not close contract 100%.

<b>Program 3</b>	1 Hz frequency	2 Hz frequency	4 Hz frequency
General movement	Forwards	A bit backwards	No
Soft or pulsed	Pulsed	Pulsed	No
Period movement(s)	Forwards and a bit backwards	Back and stops	No
Vibration	Just a bit	Yes	Yes
Observations	It moves forward.	It moves backwards really slow and vibrating	The tube does not close 100%.

<b>Program 4</b>	1 Hz frequency	2 Hz frequency	4 Hz frequency
General movement	Forwards	Forwards	No
Soft or pulsed	Pulsed	Pulsed	Pulsed
Period movement(s)	It goes forward almost the whole period and stops just for short time.	It goes forward and then stops.	Forward and backwards
Vibration	No	No	No
Observations	The fluid is pumped really fast.	It pumps well.	The tube does not close 100%.

<b>Program 5</b>	1 Hz frequency	2 Hz frequency	4 Hz frequency
General movement	Forwards	No	No
Soft or pulsed	Pulsed	Pulsed	No
Period movement(s)	Forward long and backwards long	Forward long and backwards long	No
Vibration	No	No	Yes
Observations	A bit irregular.		The tube almost does not close.

<b>Program 6</b>	1 Hz frequency	2 Hz frequency	4 Hz frequency
General movement	Forwards	Forwards	Forwards
Soft or pulsed	Pulsed	Pulsed	Pulsed
Period movement(s)	Forwards except in phase two of the period the movement is backwards.	Long forward and back a bit	Forward and back a bit
Vibration	No	No	No
Observations	The general movement is less than with the other two frequencies.	The fluid is well pumped.	The fluid is well pumped.

The following programs were tested with slower frequencies because they have many more pulses. If the period stays constant and there are more pulses, the pulses will have to be shorter in time. If the pulses are shorter in time, the tube will not close until the end, it will just constrict a bit but not the whole capacity. The frequencies are 1 Hz, 0,5 Hz and 0,2 Hz. The results of the tests are in the following tables:

<b>Program 7</b>	1 Hz frequency	0,5 Hz frequency	0,2 Hz frequency
General movement	No	No	No
Soft or pulsed	No	No	Pulsed
Period movement(s)	No	No	Forward and back a bit
Vibration	Just a little bit	Just a little bit	No
Observations	The tube does not constrict to whole capacity.	The tube does not constrict to whole capacity.	Irregular, depending on which phase the fluid movement change. Because the period now is longer so the phases can be detected and differentiated easily. In some phases the fluid stays quite and in some phases the fluid moves forwards and backwards but finishes at the same place

<b>Program 8</b>	1 Hz frequency	0,5 Hz frequency	0,2 Hz frequency
General movement	No	No	Forwards
Soft or pulsed	Pulsed	Pulsed	Pulsed
Period movement(s)	Forwards (in phase 2) and backwards	In the fifth phase it goes hard	High movement forwards and backwards

	in different phases	forwards. In the other phases it goes backwards and a bit forwards.	
Vibration	No	No	No
Observations	In the period movement it goes forwards really all of a sudden and it goes backwards in different steps. The tube does not close to the maximum capacity.	High period movement but the fluid is not pumped. There is no general movement	Long period but the general movement is forwards.

<b>Program 9</b>	1 Hz frequency	0,5 Hz frequency	0,2 Hz frequency
General movement	No	No	No
Soft or pulsed	No	No	Pulsed
Period movement(s)	No	No	Steps forward and steps backwards. Quite symmetric these steps.
Vibration	Yes	Yes	No
Observations	The tube does not close to the maximum capacity.	The tube does not close to the maximum capacity.	Long period but the general movement is forwards.

<b>Program 10</b>	1 Hz frequency	0,5 Hz frequency	0,2 Hz frequency
General movement	Backwards	Forwards	No
Soft or pulsed	Pulsed	Pulsed	No
Period movement(s)	Long step backwards in phase 3.	Steps forwards. No backwards	No
Vibration	No	No	No

Observations	The tube does not close to the maximum capacity.	The period movement is softer than in the other tests done.	Too slow the frequency.
--------------	--	---	-------------------------

<b>Program 11</b>	1 Hz frequency	0,5 Hz frequency	0,2 Hz frequency
General movement	No	No	No
Soft or pulsed	No	No	No
Period movement(s)	No	No	No
Vibration	No	No	Yes
Observations	The frequency is too fast because the tube does not constrict to the maximum capacity.	The frequency is too fast because the tube does not constrict to the maximum capacity.	The frequency is too fast because the tube does not constrict to the maximum capacity.

### 6.3.3. Conclusion of the tests

Each type of current pulsed signal makes the constriction of the tube differently because it depends on the number of the pulses, how long the pulses are and the distribution of the pulses, so the sinusoidal magnetic field changes the form for each pulsed signal. In conclusion there is no perfect signal because depending on what situation the type of pumping has to be different.

In general terms, if the number of the pulses within a period of time is high the pumping is softer. So the more pulses the program has, the softer the pumping is and also the higher the frequency is, the softer it is. But if the number of pulses or the frequency is too high, the tube will not constrict to the maximum, the fluid will not be pumped and only vibration will be generated.

If the frequency or the number of pulses is too low, there will be no movement inside the tube. It will remain at the same place even if within a period the fluid can move forwards and backwards.

On one hand, some programs do not work because they have too many pulses, so they should have been tried with slower frequencies and in some tests done in the current thesis only vibration is generated.

On the other hand, some other programs would have been good to try with higher frequencies because they have not high number of pulses.

Conclusions cannot be done only observing the distribution of pulses of the signal. It would be really interesting if better and more complex tests were done to study the mechanics and kinetics of the fluid.

## 7. CONCLUSIONS

This project has been done in different steps and parts. There has been a part of hardware; a part of software and some tests has been done at the end.

A lot of knowledge has been needed to do all these parts and big part of it has been learned while doing it, so it has made the thesis more interesting and sometimes a bit harder. For example, an electric circuit was designed with the respective program of the PLC microcontroller but it was not the best version. An easier and more efficient way was possible, so the design had to be repeated, changing the output module in the PLC microcontroller and the software program.

The CoDeSys programming of the project has been much more complex than it was expected. First of all, the working and dynamics of the software had to be learned, to do this implied some time. The process of the design of the program was totally autodidact, so this means that in almost every little step some difficulties were found.

Some other tests than the ones of the MAP pump done in the current thesis could and should be done in the future; different programs can be designed with other frequencies. The diameter of the tube can be changed. The length of the tube might also affect the behavior of the fluid that is pumped. If the fluid is changed the behavior might also changed, for example it could be tried with oil, blood or some other fluids. The potential energy is another aspect that could be changed because in the tests done in this thesis it was constant because the whole tube was in the same height. More coils could be added or the current coils could move and have more distance between them. A fluid mechanics and kinetics research should be done with these tests.

This thesis was done by a biomedical engineering bachelor student and MAPs can have multiple applications in the biomedical engineering field. Many more tests and research can be done in the direction of a MAP-tube acting as a pump which could replace in the future an artery. The biocompatibility has been already proofed (Mayer et al.2013). A reduction of the diameter is possible, which is necessary for the tube to have the arteries size.

The tube composition and geometry should be studied in detail because it affects directly to the fluid movement. The tube used in the tests has a homogenous particle distribution but the same tests can be done with other particles distribution because it affects directly to the way and the speed of how it is constricted when a magnetic field is applied.

There are a lot of other possible applications in the engineering world and in our daily lives but these will develop slowly once the MAP material is more developed, more known and more manufactured.

To sum up, conclusions cannot be done only observing the distribution of pulses of the signal or changing the frequency because the tests done in this thesis are quite simple so it is not so obvious to extract some conclusions from these tests. Better tests with better analyzing and

testing devices should be done with the same programs. This thesis opens the possibility to do multiple tests and follow the research in the fluid pumping direction.

## 8. Bibliography

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[http://mpison.webs.upv.es/investigacion\\_aplicada/textos/como\\_citar\\_upv.pdf](http://mpison.webs.upv.es/investigacion_aplicada/textos/como_citar_upv.pdf)  
[consulted August 2017].
- WAGO Kontakttechnik GmbH and Co. KG (2016). 2-Channel Analog Output Module 0-10V /+-10V. *Short-circuit protected; high-side switching.*
- WAGO Kontakttechnik GmbH and Co. KG (2016). 2-Channel Digital Output Module 24 V DC. *Short-circuit protected; high-side switching.*
- AREA TECNOLÓGICA. Transistor. *Que es un transistor?*  
<http://www.areatecnologia.com/TUTORIALES/EL%20TRANSISTOR.htm> [consulted June 2017].

## **9. Annex**

### **9.1. WAGO MODULES DATA SHEETS**

[WAGO750501.pdf](#)

[WAGO750556.pdf](#)

### **9.2. Codesys programs**

[SINUSOUTPUT.pro](#)

[PROGRAM01.pro](#)

[PROGRAM02.pro](#)

[PROGRAM03.pro](#)

[PROGRAM04.pro](#)

[PROGRAM05.pro](#)

[PROGRAM06.pro](#)

[PROGRAM07.pro](#)

[PROGRAM08.pro](#)

[PROGRAM09.pro](#)

[PROGRAM10.pro](#)

[PROGRAM11.pro](#)

### **9.3. Tests videos**

[PROGRAM1\\_1HZ.mp4](#)

[PORGRAM1\\_2HZ.mp4](#)

[PROGRAM1\\_4HZ.mp4](#)

[PROGRAM2\\_1HZ.mp4](#)

[PROGRAM2\\_2HZ.mp4](#)

[PROGRAM2\\_4HZ.mp4](#)

[PROGRAM3\\_1HZ.mp4](#)

[PROGRAM3\\_2HZ.mp4](#)

[PROGRAM3\\_4HZ.mp4](#)

[PROGRAM4\\_1HZ.mp4](#)

[PROGRAM4\\_2HZ.mp4](#)

[PROGRAM4\\_4HZ.mp4](#)

[PROGRAM5\\_1HZ.mp4](#)

[PROGRAM5\\_2HZ.mp4](#)

[PROGRAM5\\_4HZ.mp4](#)

[PROGRAM6\\_1HZ.mp4](#)

[PROGRAM6\\_2HZ.mp4](#)

[PROGRAM6\\_4HZ.mp4](#)

[PROGRAM7\\_0,2HZ.mp4](#)

[PROGRAM7\\_0,5HZ.mp4](#)

[PROGRAM7\\_1HZ.mp4](#)

[PROGRAM8\\_0,2HZ.mp4](#)

[PROGRAM8\\_0,5HZ.mp4](#)

[PROGRAM8\\_1HZ.mp4](#)

[PROGRAM9\\_0,2HZ.mp4](#)

[PROGRAM9\\_0,5HZ.mp4](#)

[PROGRAM9\\_1HZ.mp4](#)

[PROGRAM10\\_0,2HZ.mp4](#)

[PROGRAM10\\_0,5HZ.mp4](#)

[PROGRAM10\\_1HZ.mp4](#)

[PROGRAM11\\_0,2HZ.mp4](#)

[PROGRAM11\\_0,5HZ.mp4](#)

[PROGRAM11\\_1HZ.mp4](#)

## 9.4. Sinusoidal electrical output signal program

### 9.4.1. Structure of the program

#### 9.4.1.1. Variables declared

```
PROGRAM PLC_PRG  
  
VAR  
  
    SIN_GEN: GEN;  
  
    FINALVALUE1: INT;  
  
    t1: TON;  
  
    t_done1: BOOL;  
  
    tt_elapsed1: BOOL;  
  
    t_elapsed1: BOOL;  
  
    tdone: TIME;  
  
    tdone1: BOOL;  
  
    telapsed1: TIME;  
  
    FINALVALUE2: INT;  
  
    tdone2: BOOL;  
  
    telapsed2: TIME;  
  
    FINALVALUE3: INT;  
  
    t2: TON;  
  
    t3: TON;  
  
    SIN_GEN1: GEN;  
  
    SIN_GEN2: GEN;  
  
END_VAR
```

#### 9.4.1.2. Algorism

The algorithm program designed is the following with Diagram Block form:

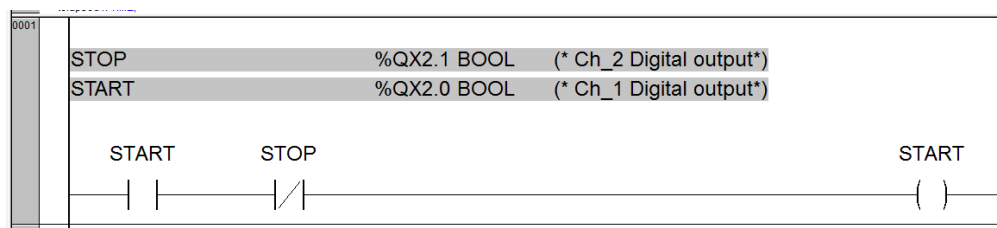


Figure 49. START and STOP for the whole program.

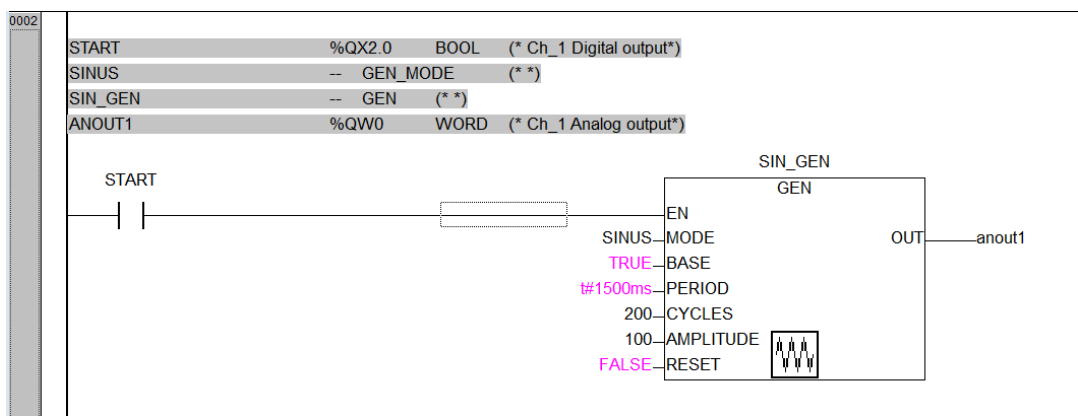


Figure 50. Sinusoidal wave generation with a period of 1500 ms.

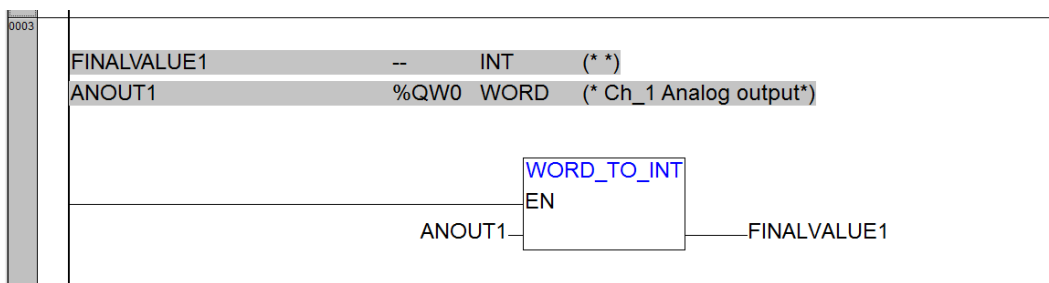


Figure 51. Conversion from Word to Integer of the ANOUT1 variable.

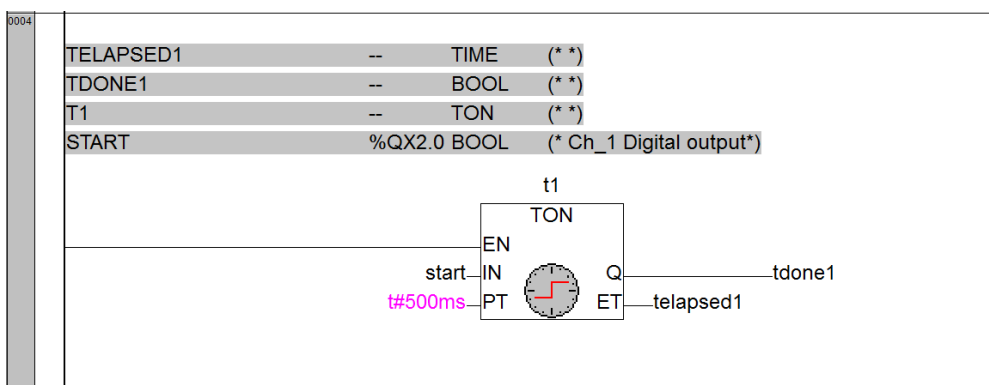


Figure 52. Timer On Delay activation with a value of 500 ms.

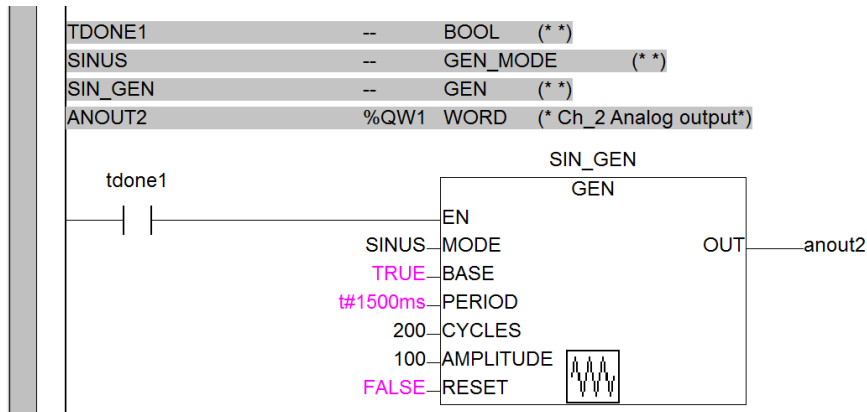


Figure 53. Sinusoidal generation for Coil 2 only if *tdone1*=TRUE.

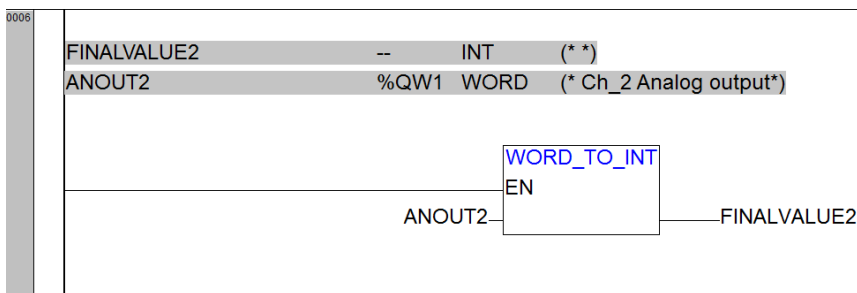


Figure 54. Conversion from Word to Integer of the *ANOUT2* variable.

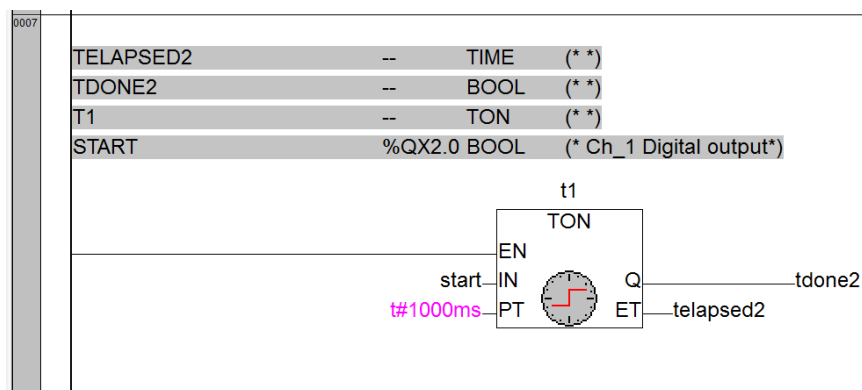


Figure 55. Timer On Delay activation with a value of 1000 ms.

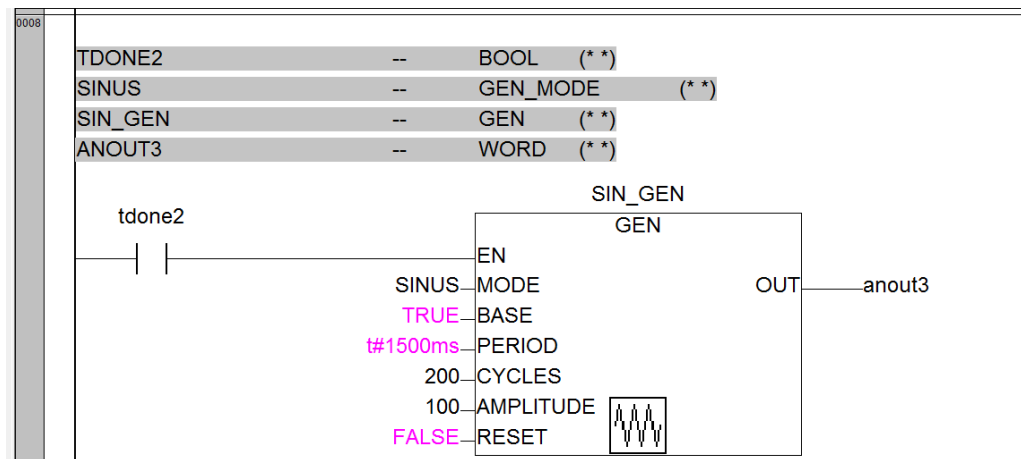


Figure 56. Sinusoidal generation for Coil 3 only if *tdone2*=TRUE.

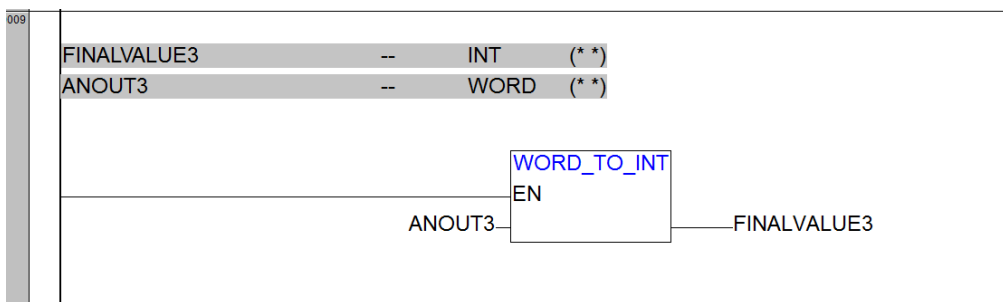


Figure 57. Conversion from Word to Integer of the *ANOUT2* variable.

## 9.5. Program 1 program

### 9.5.1. Variables

First of all the variables were declared in structured text format. They were declared following the order of apparition during the algorism:

```
PROGRAM PLC_PRG
```

```
VAR
```

```
    Period: TIME := T#20s;
```

```
    start: BOOL;
```

```
    TONA: TON;
```

```
    TONAet: TIME;
```

```
    periodA: TIME := t#3s;
```

```
    tdone13:BOOL;
```

```
    TP1: TP; period1: TIME; etime1: TIME; timer1: BOOL; Ftrig1: F_TRIG; tdone1:
    BOOL;
```

```
    TP2: TP; period2: TIME; timer2: BOOL; etime2: TIME; Ftrig2: F_TRIG; tdone2:
    BOOL;
```

```
    TP3: TP; period3: TIME; timer3: BOOL; etime3: TIME; Ftrig3: F_TRIG; tdone3:
    BOOL;
```

```
    TP4: TP; period4: TIME; timer4: BOOL; etime4: TIME; Ftrig4: F_TRIG; tdone4:
    BOOL;
```

```
    TP5: TP; period5: TIME; timer5: BOOL; etime5: TIME; Ftrig5: F_TRIG; tdone5:
    BOOL;
```

```
    TP6: TP; period6: TIME; timer6: BOOL; etime6: TIME; Ftrig6: F_TRIG; tdone6:
    BOOL;
```

```
    TP7: TP; period7: TIME; timer7: BOOL; etime7: TIME; Ftrig7: F_TRIG; tdone7:
    BOOL;
```

```
    TP8: TP; period8: TIME; timer8: BOOL; etime8: TIME; Ftrig8: F_TRIG; tdone8:
    BOOL;
```



TP9: TP; period9: TIME; timer9: BOOL; etime9: TIME; Ftrig9: F\_TRIG; tdone9: BOOL;

TP10: TP; period10: TIME; timer10: BOOL; etime10: TIME; Ftrig10: F\_TRIG; tdone10: BOOL;

TP11: TP; period11: TIME; timer11: BOOL; etime11: TIME; Ftrig11: F\_TRIG; tdone11: BOOL;

TP12: TP; period12: TIME; timer12: BOOL; etime12: TIME; Ftrig12: F\_TRIG; tdone12: BOOL;

TONBdelay: TON;

TONBet: TIME;

periodDB: TIME;

tdone13B: BOOL;

TP1B: TP; etime1B: TIME; timer1B: BOOL; Ftrig1B: F\_TRIG; tdone1B: BOOL;

TP2B: TP; etime2B: TIME; timer2B: BOOL; Ftrig2B: F\_TRIG; tdone2B: BOOL;

TP3B: TP; timer3B: BOOL; etime3B: TIME; Ftrig3B: F\_TRIG; tdone3B: BOOL;

TP4B: TP; timer4B: BOOL; etime4B: TIME; Ftrig4B: F\_TRIG; tdone4B: BOOL;

TP5B: TP; timer5B: BOOL; etime5B: TIME; Ftrig5B: F\_TRIG; tdone5B: BOOL;

TP6B: TP; timer6B: BOOL; etime6B: TIME; Ftrig6B: F\_TRIG; tdone6B: BOOL;

TP7B: TP; timer7B: BOOL; etime7B: TIME; Ftrig7B: F\_TRIG; tdone7B: BOOL;

TP8B: TP; timer8B: BOOL; etime8B: TIME; Ftrig8B: F\_TRIG; tdone8B: BOOL;

TP9B: TP; timer9B: BOOL; etime9B: TIME; Ftrig9B: F\_TRIG; tdone9B: BOOL;

TP10B: TP; timer10B: BOOL; etime10B: TIME; Ftrig10B: F\_TRIG; tdone10B: BOOL;

TP11B: TP; timer11B: BOOL; etime11B: TIME; Ftrig11B: F\_TRIG; tdone11B: BOOL;

TP12B: TP; timer12B: BOOL; etime12B: TIME; Ftrig12B: F\_TRIG; tdone12B: BOOL;

TONCdelay: TON;

TONCet: TIME;

periodDC: TIME;

```

tdone13C: BOOL;

TP1C: TP; etime1C: TIME; timer1C: BOOL; Ftrig1C: F_TRIG; tdone1C: BOOL;

TP2C: TP; etime2C: TIME; timer2C: BOOL; Ftrig2C: F_TRIG; tdone2C: BOOL;

TP3C: TP; etime3C: TIME; timer3C: BOOL; Ftrig3C: F_TRIG; tdone3C: BOOL;

TP4C: TP; etime4C: TIME; timer4C: BOOL; Ftrig4C: F_TRIG; tdone4C: BOOL;

TP5C: TP; etime5C: TIME; timer5C: BOOL; Ftrig5C: F_TRIG; tdone5C: BOOL;

TP6C: TP; etime6C: TIME; timer6C: BOOL; Ftrig6C: F_TRIG; tdone6C: BOOL;

TP7C: TP; etime7C: TIME; timer7C: BOOL; Ftrig7C: F_TRIG; tdone7C: BOOL;

TP8C: TP; etime8C: TIME; timer8C: BOOL; Ftrig8C: F_TRIG; tdone8C: BOOL;

TP9C: TP; etime9C: TIME; timer9C: BOOL; Ftrig9C: F_TRIG; tdone9C: BOOL;

TP10C: TP; etime10C: TIME; timer10C: BOOL; Ftrig10C: F_TRIG; tdone10C:
BOOL;

TP11C: TP; etime11C: TIME; timer11C: BOOL; Ftrig11C: F_TRIG; tdone11C:
BOOL;

TP12C: TP; etime12C: TIME; timer12C: BOOL; Ftrig12C: F_TRIG; tdone12C:
BOOL;

```

END\_VAR

### 9.5.2. Algorism

The algorism used, which works in the correct way is the following one:

```

periodDB:= (periodA + period/3);
periodDC:=(periodA + period/3 + period/3);
period1:= period/10;
period2:=period/10;
period3:= period/10;
period4:=period/10;
period5:= period/10;
period6:=period/10;
period7:= period/10;

```

```

period8:=period/10;

period9:= period/10;

period10:=period/10;

period11:= period/10;

period12:=period/2;

TONA(IN := start, PT:= periodA); tdone13:=tona.Q; TONAet:=TONA.ET;

TONBdelay(IN :=start, PT:=periodDB); tdone13B:=TONBdelay.Q; TONBet:=TONBdelay.ET;

TONCdelay(IN := start, PT:=periodDC); tdone13C:=TONCdelay.Q; TONCet:=TONCdelay.ET;

IF tdone12 THEN

tdone13:=FALSE;

END_IF

IF tdone12B THEN tdone13B:=FALSE;

END_IF

IF tdone12C THEN

tdone13C:=FALSE;

END_IF

TP1(IN:= tdone13, PT:= period1); timer1:= TP1.Q; etime1:= TP1.ET; Ftrig1(CLK:= timer1);
tdone1:= Ftrig1.Q;

TP2(IN:= tdone1, PT:= period2); timer2:= TP2.Q; etime2:= TP2.ET; Ftrig2(CLK:= timer2);
tdone2:= Ftrig2.Q;

TP3(IN:= tdone2, PT:= period3); timer3:= TP3.Q; etime3:= TP3.ET; Ftrig3(CLK:= timer3);
tdone3:= Ftrig3.Q;

TP4(IN:= tdone3, PT:= period4); timer4:= TP4.Q; etime4:= TP4.ET; Ftrig4(CLK:= timer4);
tdone4:= Ftrig4.Q;

TP5(IN:= tdone4, PT:= period5); timer5:= TP5.Q; etime5:= TP5.ET; Ftrig5(CLK:= timer5);
tdone5:= Ftrig5.Q;

TP6(IN:= tdone5, PT:= period6); timer6:= TP6.Q; etime6:= TP6.ET; Ftrig6(CLK:= timer6);
tdone6:= Ftrig6.Q;

```

TP7(IN:= tdone6, PT:= period7); timer7:= TP7.Q; etime7:= TP7.ET; Ftrig7(CLK:= timer7);  
tdone7:= Ftrig7.Q;

TP8(IN:= tdone7, PT:= period8); timer8:= TP8.Q; etime8:= TP8.ET; Ftrig8(CLK:= timer8);  
tdone8:= Ftrig8.Q;

TP9(IN:= tdone8, PT:= period9); timer9:= TP9.Q; etime9:= TP9.ET; Ftrig9(CLK:= timer9);  
tdone9:= Ftrig9.Q;

TP10(IN:= tdone9, PT:= period10); timer10:= TP10.Q; etime10:= TP10.ET; Ftrig10(CLK:=  
timer10); tdone10:= Ftrig10.Q;

TP11(IN:= tdone10, PT:= period11); timer11:= TP11.Q; etime11:= TP11.ET; Ftrig11(CLK:=  
timer11); tdone11:= Ftrig11.Q;

TP12(IN:= tdone11, PT:= period12); timer12:= TP12.Q; etime12:= TP12.ET; Ftrig12(CLK:=  
timer12); tdone12:= Ftrig12.Q;

IF timer1 OR timer3 OR timer5 OR timer7 OR timer9 OR timer11 THEN

do1:=TRUE;

END\_IF

IF timer2 OR timer4 OR timer6 OR timer8 OR timer10 OR timer12 THEN

do1:=FALSE;

END\_IF

TP1B(IN:= tdone13B, PT:= period1); timer1B:= TP1B.Q; etime1B:= TP1B.ET; Ftrig1B(CLK:=  
timer1B); tdone1B:= Ftrig1B.Q;

TP2B(IN:= tdone1B, PT:= period2); timer2B:= TP2B.Q; etime2B:= TP2B.ET; Ftrig2B(CLK:=  
timer2B); tdone2B:= Ftrig2B.Q;

TP3B(IN:=tdone2B, PT:=period3); timer3B:= TP3B.Q; etime3B:= TP3B.ET; Ftrig3B(CLK:=  
timer3B); tdone3B:= Ftrig3B.Q;

TP4B(IN:=tdone3B, PT:=period4); timer4B:= TP4B.Q; etime4B:= TP4B.ET; Ftrig4B(CLK:=  
timer4B); tdone4B:= Ftrig4B.Q;

TP5B(IN:=tdone4B, PT:=period5); timer5B:= TP5B.Q; etime5B:= TP5B.ET; Ftrig5B(CLK:=  
timer5B);tdone5B:= Ftrig5B.Q;

TP6B(IN:=tdone5B, PT:=period6); timer6B:= TP6B.Q; etime6B:= TP6B.ET; Ftrig6B(CLK:=  
timer6B); tdone6B:= Ftrig6B.Q;

TP7B(IN:=tdone6B, PT:=period7); timer7B:= TP7B.Q; etime7B:= TP7B.ET; Ftrig7B(CLK:= timer7B); tdone7B:= Ftrig7B.Q;

TP8B(IN:=tdone7B, PT:=period8); timer8B:= TP8B.Q; etime8B:= TP8B.ET; Ftrig8B(CLK:= timer8B); tdone8B:= Ftrig8B.Q;

TP9B(IN:=tdone8B, PT:=period9); timer9B:= TP9B.Q; etime9B:= TP9B.ET; Ftrig9B(CLK:= timer9B); tdone9B:= Ftrig9B.Q;

TP10B(IN:=tdone9B, PT:=period10); timer10B:= TP10B.Q; etime10B:= TP10B.ET; Ftrig10B(CLK:= timer10B); tdone10B:= Ftrig10B.Q;

TP11B(IN:=tdone10B, PT:=period11); timer11B:= TP11B.Q; etime11B:= TP11B.ET; Ftrig11B(CLK:= timer11B); tdone11B:= Ftrig11B.Q;

TP12B(IN:=tdone11B, PT:=period12); timer12B:= TP12B.Q; etime12B:= TP12B.ET; Ftrig12B(CLK:= timer12B); tdone12B:= Ftrig12B.Q;

IF timer1B OR timer3B OR timer5B OR timer7B OR timer9B OR timer11B THEN

do3:=TRUE;

END\_IF

IF timer2B OR timer4B OR timer6B OR timer8B OR timer10B OR timer12B THEN

do3:=FALSE;

END\_IF

TP1C(IN:= tdone13C, PT:= period1); timer1C:= TP1C.Q; etime1C:= TP1C.ET; Ftrig1C(CLK:= timer1C); tdone1C:= Ftrig1C.Q;

TP2C(IN:= tdone1C, PT:= period2); timer2C:= TP2C.Q; etime2C:= TP2C.ET; Ftrig2C(CLK:= timer2C); tdone2C:= Ftrig2C.Q;

TP3C(IN:=tdone2C, PT:=period3); timer3C:= TP3C.Q; etime3C:= TP3C.ET; Ftrig3C(CLK:= timer3C); tdone3C:= Ftrig3C.Q;

TP4C(IN:=tdone3C, PT:=period4); timer4C:= TP4C.Q; etime4C:= TP4C.ET; Ftrig4C(CLK:= timer4C); tdone4C:= Ftrig4C.Q;

TP5C(IN:=tdone4C, PT:=period5); timer5C:= TP5C.Q; etime5C:= TP5C.ET; Ftrig5C(CLK:= timer5C); tdone5C:= Ftrig5C.Q;

TP6C(IN:=tdone5C, PT:=period6); timer6C:= TP6C.Q; etime6C:= TP6C.ET; Ftrig6C(CLK:= timer6C); tdone6C:= Ftrig6C.Q;

TP7C(IN:=tdone6C, PT:=period7); timer7C:= TP7C.Q; etime7C:= TP7C.ET; Ftrig7C(CLK:= timer7C); tdone7C:= Ftrig7C.Q;

TP8C(IN:=tdone7C, PT:=period8); timer8C:= TP8C.Q; etime8C:= TP8C.ET; Ftrig8C(CLK:= timer8C); tdone8C:= Ftrig8C.Q;

TP9C(IN:=tdone8C, PT:=period9); timer9C:= TP9C.Q; etime9C:= TP9C.ET; Ftrig9C(CLK:= timer9C); tdone9C:= Ftrig9C.Q;

TP10C(IN:=tdone9C, PT:=period10); timer10C:= TP10C.Q; etime10C:= TP10C.ET; Ftrig10C(CLK:= timer10C); tdone10C:= Ftrig10C.Q;

TP11C(IN:=tdone10C, PT:=period11); timer11C:= TP11C.Q; etime11C:= TP11C.ET; Ftrig11C(CLK:= timer11C); tdone11C:= Ftrig11C.Q;

TP12C(IN:=tdone11C, PT:=period12); timer12C:= TP12C.Q; etime12C:= TP12C.ET; Ftrig12C(CLK:= timer12C); tdone12C:= Ftrig12C.Q;

IF timer1C OR timer3C OR timer5C OR timer7C OR timer9C OR timer11C THEN

do2:=TRUE;

END\_IF

IF timer2C OR timer4C OR timer6C OR timer8C OR timer10C OR timer12C THEN

do2:=FALSE;

END\_IF